

# Ultrasonic Parameters as a Function of Absolute Hydrostatic Pressure.

## I. A Review of the Data for Organic Liquids

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(Received 16 February 2000; revised 16 November 2002; accepted 9 December 2002; published 9 September 2003)

This review provides an overview of experimental results involving ultrasonic parameters as a function of absolute hydrostatic pressure in organic liquids. Major topics of discussion include the pioneering work of Litovitz and Carnevale involving deduction of the chemical and structural properties of liquids from acoustical properties as a function of pressure; modern general ultrasonic studies of a broad range of organic liquids; work accomplished by Russians and others from the former Soviet block countries, particularly the work headed by Otpuschennikov at the Kursk Pedagogical Institute; the studies involving refrigerants published by Takagi at the Kyoto Institute of Technology; tribological and petroleum industry studies related to oils; Brillouin scattering experiments; and thermodynamic methods of  $B/A$  measurement. The importance of ultrasonic parameters as a function of pressure to the understanding of a variety of processes is highlighted. A table of 325 liquids and liquid mixtures with a total of 366 entries indexed by chemical name is provided. Publications involving a specific liquid are cited within the table under the entry for that liquid, with the author's name, aim of the study (e.g., speed of sound or absorption studies), methodology, and pressure/temperature ranges of the experimentation also given (197 references). © 2003 American Institute of Physics.  
[DOI: 10.1063/1.1555588]

Key words: absorption; Brillouin; organic liquid; pressure; speed of sound; ultrasonic; ultrasound.

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### 1. Introduction

The effects of absolute hydrostatic pressure on acoustical parameters such as sound speed and absorption in liquids have not been previously reviewed. This contrasts with the particularly well-researched results available for the effects of absolute hydrostatic pressure on electromagnetic waves in liquids. [Excellent texts include those by Isaacs (1981); Bradley (1963); and Hamann (1957).] The lack of readily organized reference material for acoustics is regrettable, because an understanding of the pressure dependence of sound speed, absorption, and relaxation frequencies can provide valuable information as to transport quantities such as fluid viscosity and thermal conductivity, along with ratios of specific heats, clues as to the structure of the liquid, and knowledge about a host of other constants and parameters of importance in modeling acoustical propagation processes in fluids as different as ether, blood, and liquid krypton. Sound propagation is unique in that it is an adiabatic process: thus, sound speed data give direct and precise information on the adiabatic properties of a liquid. Additionally, sound speed is closely related to derivatives of the equation of state. Therefore, the precision of these derivatives is often substantially better when they are deduced from the speed of sound rather than obtained from the analysis of classical  $pVT$  data.

The pressure dependence of acoustical parameters is of interest to a wide range of disciplines, ranging from medicine (as for example *in vitro* studies of the nonlinearity parameter,  $B/A$ , in aqueous buffers; protein solutions; lipid

oils; and emulsions); to oceanography and geology (the propagation of sound in the high pressures found in ocean waters and in petroleum cuts); mechanical engineering (the characterization of refrigerants); tribology (the propagation of sound as related to viscosity in pressurized liquids); and to fundamental chemistry and physics (the use of sound speed and absorption to define compressibility, specific heat ratio, and other parameters in a wide variety of liquids as a function of pressure).

This paper reviews extant literature pertaining to the effect of absolute hydrostatic pressure on experimentally measured ultrasonic parameters related to sound speed and absorption in organic liquids. Studies by the various researchers are introduced in historical fashion. Where appropriate, the body of work of a given researcher or group of researchers is discussed as a whole, even though other researchers may have contributed studies during the same time period.

Although this review covers a unified topic, it can be difficult to find relevant literature, as references are scattered across a broad spectrum of sources, with a sizeable component unavailable in English. As a result, researchers working with acoustical parameters of a given liquid as a function of pressure are sometimes unaware of previous work in the same area. This review is an attempt to rectify the situation for future researchers.

This review does not cover scattering, reflection, or transmittance through bubbles as, for example, the effect of static pressure on the acoustic transmittance of Alburnex® microbubble solutions [e.g., Brayman (1996) and references therein]. Neither does the review specifically focus on instrumentation, although some mention is made of the techniques used to obtain quoted results. Internal pressures and their relationship to the speed of sound, [as for example, the work of Suryanaraya (1993) and Pugazhendhi and Suryanarayana (1990)], are not included in this work. Also, the study of the speed or absorption of sound as a function of its proximity to certain liquid to solid and liquid to vapor transition regions, rather than as a straightforward function of pressure, is not a focus of this review. Finally, as the review centers solely around liquids, no mention is made of results pertaining to dense gases. Some results are included for dilute solutions of macromolecules [Bohidar (1989c)] and for liquid mixtures containing gas [e.g., octane with nitrogen; Daridon, Lagourette, and Xans (1994). Table 1 provides a summary of all relevant experimental work discussed in this review—it should be noted that the review focuses on experimental results, not on the various theories and models developed to explain and use those results. A cogent, if somewhat dated, introduction to theoretical work in this area can be found in Van Itterbeek (1965).

A separate related review [Oakley *et al.* (2003)] analyzes mathematic models of experimental results for speed of sound data, as opposed to the experimental data review presented in this article. The related review paper computes and presents in tabular form polynomial expressions  $c(p) = \sum_{i=0}^n a_i p^i$  for the speed of sound as a function of pressure for 68 organic liquids. These results allow for straightfor-

ward comparison of the differences in speed of sound as a function of pressure between different types of liquids (e.g., benzene versus hexane) as well as different researchers working with the same liquid. The review also contains an analysis of error in the polynomial fit, as well as a discussion of experimental error, the later of which is also directly relevant to this paper.

## 2. Early Studies (1930s through 1940s)

An increase in the hydrostatic pressure in a liquid generally increases the speed of sound. This was seen in even the first studies of sound speed in liquids as a function of hydrostatic pressure, which began with those of Swanson in 1933. [Swanson (1933); Swanson (1934); Swanson and Hubbard (1934)]. Swanson measured the pressure coefficients of the speed of sound for nine organic liquids ( $C_2H_5Br$ ,  $CCl_4$ ,  $CHCl_3$ ,  $C_2H_5OC_2H_5$ ,  $C_5H_{12}$ ,  $CS_2$ ,  $C_6H_6$ ,  $C_7H_8$ , and  $C_6H_5NH_2$ ), which were chosen to provide a wide range of densities, compressibilities, viscosities and sound speeds. In the relatively small pressure range of the experiments (0.1–34.3 MPa), a nearly linear relationship between pressure and sound speed was both anticipated and observed. Pentane and ether showed approximately twice the variation of speed with pressure displayed by the remaining seven liquids.

Swanson modeled the results theoretically for  $C_2H_5Br$ ,  $C_2H_5OC_2H_5$  and  $CS_2$  through use of the relationship for the speed of sound based on adiabatic compressibility

$$c = (1/\rho\kappa_S)^{1/2},$$

where  $\kappa_S$  is the adiabatic compressibility, which was obtained from the relationship

$$\begin{aligned}\kappa_S &= (1/\nu)(\partial\nu/\partial P)_S \\ &= (1/\nu)[(\partial\nu/\partial P)_T + (T/C_P)(\partial\nu/\partial T)_P^2],\end{aligned}$$

where, in the latter equation,  $\nu$  is the specific volume ( $1/\rho$ ),  $P$  is the pressure,  $T$  is the absolute temperature, and  $C_P$  is the specific heat capacity at constant pressure, which was presumed to be constant in throughout the given pressure range. The results of this expression were in reasonable agreement with experimental results.

Talbott (1935) studied the speed of sound in diesel oil under pressures up to 41 MPa. A linear increase in sound speed with pressure was observed: theoretical values calculated from  $(1/\rho\kappa_S)^{1/2}$  were higher than experimentally obtained values.

Studies of the speed of sound as a function of pressure at room temperature continued with those of Biquard in later 1930s, using an optical diffraction method. Some preliminary attempts to model sound speed as a function of pressure were published in Biquard (1936). Subsequently, benzene, toluene, methyl acetate, and carbon tetrachloride were examined utilizing ultrasound at 10 MHz with pressures up to 63

MPa [Biquard (1938)]. Much as Swanson had observed previously, Biquard found a linear relationship between sound speed in the liquid phase and pressure. Accuracy was of the order of that reached by Swanson, the limit in both cases being governed by uncertain temperature fluctuations. A subsequent study [Biquard (1939)], showed that absorption at 6.92 MHz in toluene decreased as a function of pressures between 0.1 and 80 MPa. Experimental results at 50 MPa differed from the theoretical absorption of Stokes (due to viscosity) by 19%.

### 3. Work from the 1950s to the Late 1960s—The Pioneering Efforts of Litovitz and Carnevale

World War II interrupted research in general on the effects of pressure on acoustical parameters. Publication resumed with Kittel's theoretical examination of ultrasonic propagation in liquids, which was based on the free volume model of the liquid state [Kittel (1946)]. (Kittel's intuitive description of pressure is also worth noting. He understood the pressure  $p$  to be made up of two terms, one representing the effect of the attractive intermolecular forces and the other representing the external applied pressure. If intermolecular potential energy were to be altered by removing the attractive part of the potential while leaving the repulsive part, the "internal pressure" could then be regarded as that pressure which would compress the system to the volume actually occupied.)

Kittel's theorizing in the 1940s gave way to resumed experimentation in the 1950s. Lacam (1954) obtained experimental results for the variation of sound speed in propane as a function of temperatures ranging between 25 and 225 °C, and pressures up to 111 MPa. Lacam (1956) provided a brief historical overview of investigative efforts involving the propagation of ultrasound in fluids as a function of pressure and temperature, and published results achieved by the method of defraction of light for ultrasonic speeds in propane and methane at pressures up to 111 MPa at temperatures of 200 °C. Also in 1956, Noury published results achieved by defraction of light methods for ultrasonic speeds in propane at 585 kHz with temperatures from 75 to 125 °C, and pressures from 1 to 15 MPa.

Litovitz and Carnevale's 1955 work on sound speed and absorption in pure water was only the first of a host of efforts to obtain a more complete understanding of sound speed and absorption as a function of pressure in a variety of liquids. The results of many of these studies were recapitulated in Herzfeld and Litovitz's *Absorption and Dispersion of Ultrasonic Waves* (1959).

In their 1955 study on the pressure dependence of sound propagation in the primary alcohols, Carnevale and Litovitz made measurements of sound speed and absorption in ethyl, methyl, *n*-propyl, and *n*-butyl alcohols at pressures up to 196 MPa. Results showed that absorption decreased and sound speed increased as the hydrostatic pressure was raised. The increase in sound speed appeared to be in agreement with the

relationship of density and volume proposed by Rao (1940). The two-state theory of structural relaxation did not yield the correct pressure dependence of the absorption in the liquids: a distribution of states was suggested.

In Litovitz (1957) the theory of thermal relaxation phenomena in liquids was considered from the standpoint that the mechanism of energy transfer in the liquid was the same as in a gas. Data on ultrasonic relaxation in CS<sub>2</sub> were considered. It was found that a cell model for liquids and dense gases, in conjunction with binary collision theory, gave theoretical values for the pressure and temperature dependence of ultrasonic relaxation times which were in good agreement with experimental values.

In an accompanying paper [Litovitz *et al.* (1957)] measurements of sound absorption as a function of pressure in carbon disulfide and glycerol indicated that relaxation effects causing compressional losses in those liquids reacted differently to pressure changes. In CS<sub>2</sub> (a nonassociated liquid) the relaxation frequency increased with increasing pressure, while the relaxation frequency for glycerol (an associated liquid) decreased as the pressure was increased.

In their 1958 work, "Effect of Pressure on Ultrasonic Relaxation in Liquids. II," Litovitz and Carnevale (1958) synthesized the results of the previous work with glycerol and carbon disulfide with additional studies on acetic acid and triethylamine to form a theory of ultrasonic relaxation which was functionally dependent upon pressure. Results indicated that the *type* of relaxation, which differed in the various liquids, could have either a profound effect on the relaxation frequency as a function of pressure; or no effect at all. As Litovitz and Carnevale write:

"In glycerol the viscous relaxation effects are related to the motion of the molecule from one lattice site to another [Andreae and Lamb (1951)]. As the pressure is raised and the density is increased, it becomes more difficult for a molecule to jump from one site to another in the lattice and the time between jumps increases. Thus, the relaxation frequency for intermolecular structural rearrangements that involve molecular motion should decrease with increasing pressure."

"In CS<sub>2</sub> the relaxation effect is due to a perturbation in the equilibrium between vibrational and kinetic degrees of freedom. The relaxation time is here determined by two factors: (1) the efficiency of a collision exciting or de-exciting an internal degree of freedom and (2) the number of collisions per second. The effect of increasing pressure is to increase the number of collisions per second without affecting the collision efficiency. It is for this reason that the relaxation frequency increases with increasing pressure in CS<sub>2</sub>."

"The pressure independence of the relaxation frequencies in triethylamine and acetic acid indicates that neither vibrational-translational relaxation nor structural relaxation of the liquid lattice is involved in these liquids. This conclusion is in agreement with the assumption made by Heasall and Lamb that the loss in triethylamine is due to a rotational isomeric effect. This mechanism can cause ultrasonic relaxation owing to the finite transition rates from one equilibrium configuration to another. It was assumed by Heasall and



Lamb that the volume difference between the two states is negligible and that the important contribution to the loss is related to the difference in enthalpy between the two isomeric forms.”

“The pressure independence of the relaxation frequency in triethylamine indicates that the transition rate from one rotational isomeric form to another is not limited in any way by the rate of transfer of energy from neighboring molecules. For example, the molecule does not need to await a collision to knock it from one isomeric form to another. The process appears to be completely intramolecular and the necessary energy for the transition is obtained from coupling to other internal degrees of freedom.”

Studies on organic liquids were also expanded by those of Mifsud and Nolle (1956). Here the ultrasonic speed and absorption for carbon tetrachloride, benzene, and carbon disulfide were measured by a pulse-reflection method at several temperatures in the gauge pressure range of 0–137.8 MPa. In these studies, the speed increased with pressure by a factor of about 1.4, while the relative absorption decreased to about 0.4 times the atmospheric-pressure value. Both structural and thermal relaxation models were examined in an attempt to describe experimental results. Although a revised structural relaxation theory was found to be plausible in light of the results, Mifsud and Nolle felt that the study tended to confirm the thermal relaxation theory of excess absorption in nonassociated liquids.

Richardson and Tait (1957) made measurements of sound speed and attenuation in a number of organic liquids at pressures up to 68.9 MPa. Carbon tetrachloride and benzene were chosen as being typical of nonassociated liquids showing “anomalous absorption;” ether and pentane as liquids with high compressibility at room temperature; carbon dioxide and monofluorotrichloromethane (Freon 11) as typical fluids which are vapors at n.t.p.; and glycerine as typical of a liquid having a high shear viscosity. The purpose of the work was to provide experimental data that could form a basis for theoretical discussion.

Results for the speed of sound in carbon tetrachloride and benzene (taken at 3 MHz) were in excellent agreement with those of Biquard’s higher frequency measurements (10 MHz); Swanson’s points, taken at 193.7 kHz, were more scattered and bore a different slope. In comparison with results obtained for water, the two striking features of the curves for benzene and carbon tetrachloride were the greater slope and the curvature. Over the measured temperature range the ratio of the speed of sound as a function of pressure to that at atmospheric pressure increased steadily with temperature. This was in accordance with the observed increase in compressibility with temperature for these liquids.

As the absorption of pentane and ether was much less than those of benzene and carbon tetrachloride, it was necessary to measure it at a higher frequency: 12 MHz. Some lack of reproducibility of the results was noted, attributed to scattering of the radiation by thermal inconsistencies such as occur near the critical state.

Sound speed isotherms for CO<sub>2</sub> and CCl<sub>3</sub>F showed the

sharp curves characteristic of fluids at supercritical pressures. Glycerine, the last substance characterized in the experiments, was typical of the rather few liquids which exhibit a large viscosity both to shear and to ultrasonic waves. Both speed and absorption values were noted.

In other work, McSkimin (1957) published the results of experimental studies of both sound speed and attenuation as a function of pressures up to 145 MPa for carbon tetrachloride and to 359 MPa for silicone fluids, at temperatures ranging from 5 to 50 °C. Eden and Richardson (1960) published a comprehensive study of sound speed in alcohols, monohalogenated benzenes, acetone, hexanes, isopentane, and acetaldehyde at temperatures between 0 and 50 °C, and pressures up to 68 MPa. Absorption was also studied. Finally, Wilson and Bradley (1964) extended earlier work on the effects of pressure and temperature on the speed of sound in distilled water to study similar effects in methyl, ethyl, *n*-propyl, and *n*-butyl alcohol for temperatures and pressures in the ranges of 0–60 °C and 0–96 MPa. The data obtained for ethyl alcohol were used to compute the ratio of specific heats for this alcohol.

#### 4. Modern General “Western” Studies (Since 1967) Using Pulse-Echo Techniques

For discussion purposes, it is worthwhile to break work done from the late 1960s onwards into three separate groups. The first group consists of a number of disparate researchers and research groups in Western Europe and the United States. The second group centers on the work of the Soviet block countries, largely dominated by the prolific output of Otpuschennikov and his co-workers at the Kursk Pedagogical Institute. The third group consists of the many studies of the research efforts of Takagi in Japan. In this section, the first group will be discussed.

Using the somewhat artificial dividing line of 1967, “modern” Western efforts can be seen as beginning with Boelhouwer (1967). Sound speeds were studied in liquid hexane, heptane, octane, nonane, dodecane, and hexadecane in a temperature range from –20 to 200 °C and at pressures up to 140 MPa using a 2 MHz pulse echo technique. Accuracy was estimated to 1%: the results were used to derive adiabatic compressibility. The pulse technique involving a fixed path length was described in some detail. In one of the earliest supercooled studies, Van Iiterbeek *et al.* (1967) studied the speed of sound in liquid methane as a function of pressure for various temperatures between –182 and –82 °C with pressures up to 20 MPa. It was discovered that for isotherms near the critical point, the change of sound speed with change in pressure became very large and had a high degree of pressure dependence.

In 1969, Hawley and co-workers [Hawley, Allegra, and Holton (1970)] performed a series of experiments at Harvard under pressures up to 522 MPa on water, methyl alcohol, ethyl alcohol, *n*-propyl alcohol, *n*-butyl alcohol, eugenol, carbon tetrachloride, *n*-hexane, and toluene. The emphasis was primarily on documenting the effect on the attenuation

and related acoustic parameters when high hydrostatic pressures were applied to the liquid. Absorption characteristics were reproduced to  $\pm 3\%$  in separate experiments. Absorption coefficients and values for speed of sound were found to be within about 5% and 0.3%, respectively, of those published by Carnevale and Litovitz (1955) over the experimental range for which comparison was possible.

An example of the use of the results of acoustical parameters as a function of pressure for a greater theoretical understanding of the structure of liquids was given in Allegra, Hawley, and Holton (1970). In this study, the absorption and speed of sound as a function of pressures ranging up to 981 MPa were observed in toluene and hexane at 30 °C. Toluene was chosen because the absorption attributable to shear viscosity increases quite rapidly at high pressures, dramatizing the increase with pressure of viscous contributions to the total absorption. Hexane was of interest because, at atmospheric pressure, the ratio of the total absorption to the absorption resulting from shear viscosity is constant over a wide range of temperatures. (This was felt to indicate a large ratio of compressional to shear viscosity.) In the analysis, the absorption of ultrasound as a function of pressure in *n*-hexane and toluene was resolved into its various contributions by estimating the ratio of compressional to shear viscosity  $\eta_c/\eta_s$ . At lower pressures, the viscous contributions were small, and the separation of the vibrational contribution was relatively insensitive to the choice of  $\eta_c/\eta_s$ , whereas at higher pressures, the viscous contributions dominated, making the resolution of the vibrational contribution very sensitive to the choice of  $\eta_c/\eta_s$ .

In a study involving a completely different type of experimental apparatus, Collings and McLaughlin (1970) measured viscosities in benzene, cyclohexane, carbon tetrachloride, isopentane, and *n*-pentane at temperatures of 30–50 °C with pressures up to 6.86 GPa using a torsional vibrating quartz crystal. It was concluded that the torsional crystal method was capable of accuracies of 0.5%.

Utilizing more conventional pulse echo equipment, Nomura, Kuroki and Miyayara (1971), published a study of the speed of sound in methyl, ethyl, *n*-propyl, and *n*-butyl acetate. Pressures up to 30 MPa were measured, with temperatures ranging from 5 to 35 °C. The speed of sound in these esters was found to increase parabolically with pressure. From these results, the nonlinearity parameters  $B/A$  were determined. These parameters were found to be almost entirely due to the pressure dependence of the speed of sound and independent of the temperature.

Houck and Heydemann (1971) published a study involving dilatometric and ultrasonic measurements at pressures to 2000 MPa for aviation instrument oil, 2-methylbutane, and their mixtures. Results were related to the density, relative volume, and isothermal bulk modulus of the mixtures. Houck (1974) published high pressure measurements of density, speed of sound, and bulk moduli of pentane and 2-methylbutane and their mixtures.

In the late 1970s, Bobik, Niepmann, and others at the Institut für Thermo- und Fluidodynamik at Ruhr-Universität Bo-

chum initiated a series of studies using pulse echo techniques with a single 2 MHz quartz transducer to study the thermodynamic quantities of pure liquids. In 1978, results were published for benzene [Bobik (1978)] for sound speeds at temperatures between 10 and 190 °C, and pressure up to 62 MPa. A polynomial was given for the whole range as a function of temperature and pressure of the form

$$c = \sum_{i=0}^4 \sum_{j=0}^4 a_{ij} p^i T^j.$$

The mean deviation of the polynomial fits was  $\pm 0.5 \text{ m s}^{-1}$ . Within their greater error intervals, older data were in agreement with the measurements.

In 1979, similar results were published for carbon tetrachloride for sound speed between  $-8$  and  $162$  °C and up to 62 MPa [Bobik *et al.* (1979)]. The mean deviation of the polynomial fits was below  $\pm 0.6 \text{ m s}^{-1}$ . Similar results were published by Niepmann and Schmidt (1980) for octamethylcyclotetrasiloxane, which showed a nominal value for sound speed of  $900.84 \text{ m s}^{-1}$  at 30 °C. Propane and *n*-butane were investigated in a Neipmann (1984), while liquid chlorodifluoromethane ( $\text{CHClF}_2$ ) and dichloromethane ( $\text{CH}_2\text{Cl}_2$ ) were explored in Neipmann *et al.* (1987).

Van't Klooster, Muringer, and Trappeniers (1980) used experimental results on the speed of sound to test the validity of several equations of state. The regime between  $-95$  and  $50$  °C and pressures up to 260 MPa was studied. Muringer, Trappeniers, and Biswas (1985) went on to measure the effect of pressure on the speed of sound and density of toluene and *n*-heptane at pressures up to 260 MPa, at temperatures ranging between  $-88$  and  $47$  °C. The density, isothermal compressibility, isobaric thermal expansion, and specific heat at constant pressure of both liquids were evaluated from the measured sound speed, following a method devised earlier.

In the late 1980s and early 1990s, Lainez, Zollweg, Streett, and co-workers spearheaded an interesting series of sound speed measurements for a number of different liquids. Experiments were carried out at 3 MHz with a newly constructed direct-weighing apparatus designed for use from  $-153$  to  $257$  °C with pressures up to 400 MPa. Lainez *et al.* (1987) conducted volumetric and speed-of-sound measurements in tetrachloromethane (carbon tetrachloride). Results compared well with published values, including those of Hawley *et al.* (1970), Richardson and Tait (1957), Makita and Takagi (1968), and Bobik *et al.* (1979). [McSkimmin (1957) and Mifsud and Nolle (1956), who provided only graphical results, could not be included in the comparison.]

Lainez *et al.* (1989) studied trichlorofluoromethane at four temperatures between 80 and 140 °C and pressures up to 210 MPa. A 14-parameter rational polynomial fitted the ( $p, c, T$ ) results with an average error of 0.040%. Lainez, Zollweg, and Streett (1990) studied *n*-pentane and 2,2-dimethylpropane. Rational polynomials were used to fit the ( $p, c, T$ ) results, with root-mean-square deviations of 0.036 and 0.046 for *n*-pentane and 2,2-dimethylpropane, respectively. Results were compared with previous studies of the speed of sound in pentane published by Otpushchennikov

*et al.* (1974; speed), Houck (1974), Melikhov (1985), Belinskii and Ikramov (1973), and Ismagilov and Ermakov (1982). [Other worthwhile earlier efforts involving the speed of sound in liquid pentane as a function of varying pressure include Younglove (1981) and Lacam (1956).]

Benzene and cyclohexane were the subjects of a study by Sun *et al.* (1987). In this work, a phase comparison pulse echo method with two reflectors was used to determine the speed of sound for both benzene and cyclohexane at temperatures ranging between 10 and 50 °C, and pressures ranging up to 170 MPa for benzene and 80 MPa for cyclohexane. The density, isothermal compressibility, isobaric thermal expansion, and specific heat at constant pressure were evaluated from the measured sound speeds. Results were compared with previous published studies of Langguth *et al.* (1977), Takagi and Teranishi (1984a), (1984b, 1984c), and Bobik (1978). Sun *et al.*'s experimental apparatus had the advantage over the single reflector pulse-echo method in that there were no unwanted reflections of the sound pulse from the transducer and, consequently, the uncertainty in the transit time determination was very small.

Using a new method of computational analysis, Biswas and ten Seldam (1992) derived the equation of state and heat capacity for methane at lower temperatures (−125–25 °C) and at greater pressures than any previous comprehensive study: up to 1000 MPa. Using the stepwise construction of *p*–*T* isochores, densities were predicted with an uncertainty no greater than 0.14%. Results were in agreement with those of Setzmann and Wagner, but the difference in the results increased with decreasing temperature.

## 5. Work by Russians and Those of the Former Soviet Block Countries (1950s through 1980s)

The published work of the former Soviet block countries is somewhat difficult to access, as a substantial portion is in Russian, with some documents being unavailable through Western sources. An overview of some of the broad-ranging results follows in chronological sequence. The careful reader is referred to Melikhov (1982) for the most thorough previous review (albeit in Russian) of partially relevant subject matter. Also worthwhile is the annual collection *Ul'trazvuk i Termodinamicheskie Svoistva Veshchestva*, (Kurskiĭ Gosudarstvennyĭ Pedagogicheskii Institut); the collected editions of *Ul'trazvuk i Fiziko-chimicheskie Svoistva Veshchestva*; as well as the periodical *Nauchnye Trudy* (Kurskiĭ Gosudarstvennyĭ Pedagogicheskii Institut. Early texts of historical interest include Kudryavtsev (1952) and Suslov and Kudryavtsev (1955).

Nozdrev's text *The Use of Ultrasonics in Molecular Physics* appeared in English in 1965 [Nozdrev (1965)]. This work, a translation from the Russian, contained the results of several previous years of research from the combined laboratories of molecular acoustics of the N. K. Krupski Moscow Provincial Pedagogical Institute and of Molecular Physics of the University of Moscow. Pressurization vessels capable of

achieving pressures up to 40.5 MPa and temperatures up to 600 °C were available. However, relevant studies were primarily concerned with the variation of the speed of sound as a function of temperature in organic liquids at their saturated vapor pressures. Liquids so studied included the aliphatic and aromatic hydrocarbons, acetates, formates, monohydric alcohols, and halogenated benzenes. The few studies directly relating sound speed to pressure were performed only in organic vapors and gases.

Otpuschennikov, Badalyan, Shoitov and a host of other Russians began publishing in the late 1960s and early 1970s, primarily through work accomplished at the Kursk State Pedagogical Institute under Otpuschennikov's direction. Shoitov and Otpushchennikov (1968) reported sound speed in *n*- and *iso*-butyl alcohol at pressures up to 50 MPa and temperatures between 50 and 110 °C. These results were compared with results for nine other liquids from the literature to show that a linear relation exists between pressure and sound speed at constant temperature. Badalyan, Otpushchennikov, and Shoitov (1970) provided experimental results for the speed of sound in *n*-octane and *n*-decane at pressures up to 118 MPa and temperatures between 30 and 140 °C. The speed was found to be nonlinear along isotherms. Badalyan, Otpushchennikov, and Shoitov (1971) provided results for the measurement of sound speed in 1-nonene, 1-octene and 1-decene at temperatures between 30 and 130 °C and pressures up to 118 MPa. An empirical equation was found to describe the temperature and pressure variation.

Otpushchennikov *et al.* (1974b) described a new type of ultrasound system and provided results for benzene up to 100 MPa, and for diethyl ether and isopropyl alcohol on the saturation line. An equation was derived to describe the relationships between the sound speed and pressure and density. Otpushchennikov *et al.* (1974a) described investigations into the speed of sound in *n*-pentane at pressures up to 203 MPa. Sysoev, Otpushchennikov, and Badalyan (1976); Sysoev and Otpushchennikov (1976a) (1976b); Sysoev and Otpushchennikov (1977); and Sysoev (1977) described the thermodynamic properties of various alcohols based upon experimental results for the speed of sound at pressures to 990 MPa. [Sysoev's equipment was described in Sysoev and Otpushchennikov (1976a), which included some data for *n*-propyl and *n*-butyl alcohol.] Sysoev and Otpushchennikov (1979) provided tabular results for similar speed-of-sound experiments in *iso*-propanol, *n*-pentanol, *n*-hexanol, *n*-heptanol, *n*-dodecanol, 1,3-propanol, diethyl ether, carbon tetrachloride, and polymethylsiloxane (PMS-1000).

Belinskii and Ikramov (1973) published a comprehensive investigation of the propagation speed and coefficient of absorption of ultrasound, along with the shear viscosity, density, and dielectric constant of *n*-pentane at pressures from 0 to 784 MPa along the 20, 30, and 40 °C isotherms. The experimental results were used to calculate the nonlinear parameters

$$Ra = \left[ \frac{\partial \ln c}{\partial \ln \rho} \right]_T, \quad \Gamma_{ad} = \frac{\partial(\rho c^2)}{\partial P}$$



as well as the activation energies of the shear and bulk viscosities.

Atoyan and Mamedov (1975a) (1975b) published results for methylhexylketone using a new method of compression that allowed for broader region of ultrasonic parameter measurement. Conducted at temperatures from 0 to 200 °C with pressures from 0.1 to 16.2 MPa, the speed of sound and the density increased exponentially with pressure, and the coefficient of absorption decreased exponentially with pressure.

Kagramanyan and Badalyan (1978) described experimental apparatus for the measurement of the speed of sound in liquids at pressures up to 203 MPa at temperatures ranging from 30 to 100 °C with error of no more than 0.2%. The speed of sound in *n*-hexane and polyethylsiloxane-2 were examined as a function of pressure. Kagramanyan continued on to publish several other studies of polyethylsiloxanes as a function of pressure with Badalyan and others. These studies included Kagramanyan, Badalyan and Otpushchennikov (1978); Kagramanyan, Badalyan, Otpushchennikov (1979); Kagramanyan and Badalyan (1979); Kagramanyan and Bagdasaryan (1983); Kagramanyan and Badalyan (1983a); Kagramanyan and Badalyan (1983b)—this later work included a study of polymethylsiloxanes.

Pevnyi and Otpushchennikov (1980a) provided information as to an experimental apparatus for studying acoustic and viscosity properties of liquids over a wide range of temperatures and pressures. Results for *iso*-propanol, *n*-butanol, benzol, and toluol were provided. Pevnyi and Otpushchennikov (1980b) provided sound speed for dibutyl, dipropyl and di-*iso*-propyl ether, as well as *n*-hexyl alcohol at pressures up to 800 MPa. In 1981 Pevnyi and Otpushchennikov published results for ultrasonic speed in a nonassociative liquid—butylphenyl—for pressures up to 800 MPa. The results were exactly those expected of a nonassociated organic liquid based upon the 1976 study of Sysoev and Otpushchennikov. Pevnyi (1983) provided similar results for an experimental study of the ultrasound propagation speed in dialyl ether. In the work of other researchers: Guseinov and Klimova (1983) published a study of the speed of sound in amyl propionate at pressures to 50 MPa. Makhno *et al.* (1985) studied the thermodynamic characteristics of secondary butylbenzene from 0 to 245 MPa at temperatures between 40 and 180 °C. Tsydypov and Otpushchennikov (1981) studied decalin at pressures of up to 250 MPa at temperatures between 17 and 177 °C.

Melikhov *et al.* (1976) began simply by studying the speed of sound in *n*-hexane at pressures to 300 MPa, while Melikhov *et al.* (1979) studied the speed of sound in *n*-hexane at pressures up to 588.5 MPa. Melikhov (1985) involved a much more comprehensive study of the speed of sound as a function of pressure in 12 polyatomic liquids: *n*-pentane, *n*-hexane, *n*-heptane, *n*-octane, *n*-nonane, *n*-decane, *n*-undecane, *n*-dodecane, 1-octene, 1-decene, benzene, and cyclohexane. Temperatures ranged from 30 to 160 °C, and pressures to 600 MPa.

In one of the last publications of the Kursk State Pedagogical Institute, Verveiko and Melnikov (1989) published a

study of the speed of sound in benzene, toluene, chlorobenzene, fluorobenzene, iodobenzene, 2,4-dibromotoluene, 2,4-dichlorotoluene, iodotoluene, and chlorotoluene at pressures to 600 MPa and temperatures between 20 and 150 °C. With the crumbling of the Berlin Wall and the subsequent passing of Communism in the former Soviet Union, the phenomenal output of the Kursk State Pedagogical Institute was abruptly halted. No studies were published in this area after 1989.

## 6. Takagi and Co-Workers at the Kyoto Institute of Technology (1968 through Present); Refrigerants

Takagi and his frequent collaborator, Teranishi, of the Kyoto Institute of Technology, instituted a number of studies of a variety of liquids and liquid mixtures—the group's work is so prolific as to merit separate mention. Takagi's earliest work was performed with Makita [Makita and Takagi (1968)] at Kobe University: this work examined the speed of sound in benzene and carbon tetrachloride to pressures of up to 213 and 253 MPa, respectively. Takagi (1975) studied sound speeds in chlorobenzene and nitrobenzene under pressures up to 210 MPa at temperatures from 10 to 60 °C. Takagi (1976) examined the speed of sound in aniline and cyclohexane under similar conditions. Ultrasonic speed at a constant temperature was found to increase parabolically with increasing pressure in all four liquids. Using the measured values of sound speed and *PVT* relations reported in the literature, the adiabatic compressibility, specific heat ratio, and specific heat at constant pressure were determined with a high degree of accuracy. Takagi (1978a) studied the speed of ultrasound and density of liquid *n*-alkanes under similar pressure and temperature conditions. The speed of sound for each of the three liquids studied—*n*-hexane, *n*-heptane and *n*-octane—increased with increasing pressure. The values of  $(\partial c/\partial P)_T$  at atmospheric pressure varied slightly, but converged to nearly a single value at pressures higher than 100 MPa. Takagi (1978b) (1978c) and found that ultrasonic speed in the pure components and their mixtures increased parabolically with increasing pressure. Densities, isothermal and adiabatic compressibilities, and the expansion coefficient as a function of pressure were calculated using the ultrasonic results. Takagi (1980b) explored the speed of sound in benzene+cyclohexane under pressures of up to 200 MPa. Curves of ultrasonic speed against mole fraction had a minimum in all pressure ranges. The mole fraction  $x_{\min}$  at the minimum shifted towards benzene with increasing pressure. In that same year (Takagi 1980a) measured the ultrasonic speeds of benzene+aniline and chlorobenzene+aniline at pressures from 100 kPa to 210 MPa for a temperature range of 0–102 °C. Using the measured ultrasonic speeds and calculated densities, the isentropic and isothermal compressibilities were derived.

Takagi (1981) studied the ultrasonic speeds and thermodynamics of benzene+an isomeric xylene at pressures up to 200 MPa at a temperature of 30 °C. When the values at  $x = 0.5$  were plotted against pressure, the curve for (benzene

+*p*-xylene) exhibited a smaller pressure dependence than that for (benzene+*o*-xylene), or (benzene+*m*-xylene). In 1982, Takagi and Teranishi reported in two studies the results for ultrasonic speed and thermodynamic properties of (benzene+chlorobenzene), (benzene+bromobenzene) (1982a), and (benzene+nitrobenzene) (1982b) at pressures up to 200 MPa. Takagi published three papers with Teranishi in 1984 on the study of ultrasonic speeds and densities of benzene, toluene, (chlorobenzene+nitrobenzene), and (chlorobenzene+bromobenzene) at pressures up to 200 MPa and temperatures ranging from 20 to 40 °C. The pair went on to publish three more papers in 1985 [Takagi and Teranishi (1985a), (1985b), (1985c)] on the study of ultrasonic speeds and thermodynamics for binary solutions of *n*-alkanes, (toluene+*o*-xylene), (toluene+aniline), and poly(dimethylsiloxane) with pressures up to 200 MPa. Liquid *n*-alkanes studied included *n*-hexane+*n*-decane, *n*-octane+*n*-dodecane and *n*-decane+*n*-tetradecane. Results were used to calculate thermodynamic properties, and to provide clues to the understanding of the character of binary solutions under high pressure.

Takagi and Teranishi (1986) studied sound speed in dichlorotetrafluoroethane–R114—at pressures up to 50 MPa within the temperature range 10–50 °C. A new, more accurate and higher pressure (up to 200 MPa) apparatus was devised and described in 1987 [Takagi and Teranishi (1987a)]. A subsequent set of papers [Takagi and Teranishi (1987b); Takagi and Teranishi (1988a) and (1988b)]; along with Takagi *et al.* (1989a) studied the speed of sound in mixtures of monochlorodifluoromethane and monochloropentafluoroethane, including the mixture commonly known as R502. These mixtures were measured at pressures up to 51 MPa within the temperature range 10–100 °C. (Since these fluids are considered environmentally friendly, their thermodynamic properties are important to the refrigeration industry.) Comparisons were made between the experimental quantity and estimates of the speed of sound as a function of temperature, pressure, and mole fraction obtained from various empirical equations of state applicable to refrigerants. Of primary interest was the variation of adiabatic compressibility  $\kappa_s$ , with temperature and pressure. This value can be obtained from measurements of the speed of sound  $u$  and the density  $\rho$  by use of the equation

$$\kappa_s = 1/\rho u^2.$$

This method of determining  $\kappa_s$  was first published by the same authors in a 1987 work describing a new apparatus that allowed for an easier method, the “sing-around,” of accurately measuring ultrasonic speed in compressed liquids up to 200 MPa. “Sing-around” means that the outgoing ultrasonic pulse is reflected back and also subsequently received by the same ultrasonic transducer. Using the sing-around method, Takagi *et al.* (1989b) measured ultrasonic speed in tetramethylsilane, tetraethylsilane, and tetraethoxysilane with temperatures from 10 to 100 °C at pressures up to 200 MPa. The results for ultrasonic speed correlated well with intermolecular free length. Ultrasonic speeds were measured in liq-

uid trichlorofluoromethane, 1,1-dichloro-1,2,2-trifluoroethane (Takagi 1991), and 1,2-dichloro-1,2,2-fluoroethane [Takagi, Kusunoki, and Hongo (1992)]. As a result of these studies, it was suggested that ultrasonic speeds were high for spherical molecules due to tight packing.

Ultrasonic speeds were measured in pentafluoropropyl, tetrafluoropropyl, and trifluoroethyl alcohols [Takagi and Noguchi (1992)]. The findings showed these alcohols exhibited lower speeds and less pressure dependency than did the primary alcohols. Takagi (1993) examined ultrasonic speeds in liquid difluoromethane under pressures ranging from the saturated vapor pressure to about 35 MPa, at temperatures from –30 to 100 °C. The results were compared with those for  $\text{CHClF}_2$  and  $\text{CF}_3\text{CH}_2\text{F}$ . Ultrasonic speeds were also studied in 1,1-dichloro-1-fluoroethane for pressures up to 50 MPa with temperature ranging from 10 to 100 °C [Takagi and Hongo (1993)]. In 1994, Takagi released results for a similar work on trichloromethane and dichloromethane [Takagi (1994a)]. The ultrasonic speeds in these liquids were found to have stronger pressure and temperature dependencies than that of tetrachloromethane, which has a spherical molecular structure. A subsequent paper [Takagi (1996a)] examined ultrasonic speeds in compressed liquid and vapor pressures for 1,1,1,2-tetrafluoroethane ( $\text{CF}_3\text{CH}_2\text{F}$ ) between –30 and 60 °C at pressures ranging from near the saturation line to about 30 MPa. The measurements were made using a sing-around technique employing a fixed path acoustic interferometer at 2 MHz. Ultrasonic speeds for the saturated liquid were estimated to within  $\pm 1$  m/s. Results were compared with studies of Guedes and Zollweg (1992) and the previously unpublished work of Vstushaninc and Grebenkov of the Moscow Power Engineering Institute. Takagi (1996b) studied the speed of sound in pentafluoroethane from the saturation line to about 30 MPa, with temperatures from –30 to 60 °C.

An interesting review article, unfortunately in Japanese, was published in 1994 [Takagi (1994b)]. This article reviewed experimental techniques for measuring ultrasonic speed, its behavior in liquids at high pressures, and the estimation of the liquid density from the speed data. The temperature and pressure dependencies of ultrasonic speed in halogenated benzenes were discussed. As a new attempt to estimate density from speed of sound data, the liquid molar volume for these substances was derived by means of the Peng–Robinson equation of state with reasonable accuracy.

Takagi (1997b) explored ultrasonic speeds in the liquid phase for binary mixtures of pentafluoroethane (HFC-125) and 1,1,1,2-tetrafluoroethane (HFC-134a), which are among those binary/ternary mixtures of hydrofluorocarbons (HFCs) that have been selected as the systems suitable for the replacements of chlorodifluoromethane ( $\text{CHClF}_2$ , HCFC-22) and the azeotropic mixture  $\text{CHClF}_2/\text{CClF}_2\text{CF}_3$  (R502). It was noted that the treatment of refrigerant mixtures is extremely complicated, and therefore accurate data on the thermophysical properties, especially on the composition effects, are much in demand. Results covered temperatures ranging from –30 to 60 °C and from near the saturated pressure to



about 30 MPa. The values for the speed of sound were found to increase monotonically with increasing pressure: measurements taken near the saturation line showed large pressure effects on the speed of sound and on  $(\partial u/\partial p)_T$ , especially in the high-temperature region—a result similar to that of pure substances. In the case of refrigerants, the thermophysical properties at vapor–liquid equilibria are important for system design. Therefore, for this later study, Takagi conveniently measured the bubble point pressure for the mixture by using the phenomenon of acoustic absorption observed in the measurement of the speed of sound. Ultrasonic speeds were further examined at pressures up to 30 MPa in liquid 1,1,1-trifluoroethane [Takagi (1997a)] and 1,1,1,2,2-pentafluoro-3,3-dichloropropane and 1,1,2,2,3-pentafluoro-1,3-dichloropropane [Takagi (1998)].

Takagi's efforts continue at present. He is the most long-lived and prolific researcher in the subject area of this review.

## 7. Tribological and Petroleum Industry Studies Related to Oils

The study of acoustical parameters as a function of pressure in oils is an area of great importance to both tribological issues and the petroleum industry. An overview of this area is provided here, with a discussion of oil studies using the Brillouin technique being deferred to Sec. 8.

In the earliest substantive work in this area, Matteson (1938) developed a method for determining the speed of pressure waves in petroleum oils as a function of adiabatic compressibility. Two years later, Matteson and Vogt (1940) experimentally measured the speed of sound in thirty seven oils at 38 °C and atmospheric pressure, and five oils with a temperature range of 14–99 °C and pressures from 3.5 to 41.4 MPa.

Barlow and Lamb (1959), (1967), Barlow *et al.* (1964), (1967a), (1967b), (1972), (1973), used their experimental results to verify a viscoelastic model based on the parallel association between a Newtonian fluid impedance and an elastic solid impedance. In other efforts, Philippoff (1963) ran experiments up to 100 MPa on multiple oils and polymers applying a technique developed by Mason (1947). The pressure influence on viscosity and elasticity parameters was compared, and it was noted that viscoelastic behavior was mainly governed by viscosity variations. Houck and Heydemann (1971) (*vide infra*) studied aviation instrument oil and its mixture with 2-methylbutane. Collings and McLaughlin (1972) reached 0.7 GPa on pure liquids. In the same frequency domain (60 kHz), Rein *et al.* (1972) reported good correlation between their ultrasonic results and low shear rate results for temperatures up to 150 °C. Hutton and Phillips (1972) and Hutton *et al.* (1978) published results obtained in shear and in compression on various liquids. The zero frequency shear viscosity and the infinite frequency shear modulus were given as functions of pressure and temperature.

In 1986, Bezot *et al.* (1986) employed a light scattering technique to determine sound speed in the synthetic oil 5P4E at pressures up to 200 MPa with temperatures of 26–59 °C. Ultrasonic speed was shown to increase linearly with pressure. Wang *et al.* (1988) published results of a series of experiments pertaining to the speed of sound in 8 dead crude oils, 2 refined petroleum hydrocarbons, and 1 live oil. The speed of sound in live oils were found to be lowered by the gas in solution, but the temperature and pressure behaviors remained similar to those of dead oils without gas. Fujishiro *et al.* (1992), using a newly developed high-pressure diamond-anvil cell, determined sound speed with an interferometer at approximately 20 °C for benzene, castor oil, ethanol, and BCCM (bicyclohexylcyclohexylmethane) at atmospheric pressure and up to 2400 and 6000 MPa, respectively, for ethanol and methanol.

Vergne and Roche (1991) published results obtained for the speed of sound as a function of pressure obtained through the use of a new apparatus based on the falling body viscometer principle. Results were shown for highly refined naphthenic mineral oil and silicone fluid (tetrachlorophenylmethylpolysiloxane). Pressures were varied up to 700 MPa and temperatures ranged from 25 to 150 °C. The experiments were used primarily to obtain viscosity and compressibility measurements; little detail was provided on the acoustical apparatus used. Earlier results involving the study of the complex viscosity of polymer oil systems under different temperatures and hydrostatic pressures include an interesting study by Philippoff (1963), which involved the use of a torsionally vibrating quartz crystal. Hutton *et al.* (1978) studied the rheological properties of liquid lubricants, with some results involving ultrasonic speed and absorption. In 1990, Berthe and Vergne [Berth and Vergne (1990)] published a comprehensive review of high-pressure rheology for high pressure lubrication, which included some of the results mentioned above.

Ye *et al.* (1992b) provided an overview of the burgeoning number of experimental studies for ultrasound speed in pure hydrocarbons, and compared the results of these studies with the values calculated by means of six different equations of state. Substances studied included linear alkanes from *n*-C<sub>3</sub> to *n*-C<sub>16</sub>, benzene, toluene, and cyclohexane. Ye, *et al.*'s own previous work studying *n*-decane and *n*-hexadecane at pressures of up to 60 and 70 MPa, respectively, was also included in the study [Ye *et al.* (1990)]. A study of the speed of sound in binary mixtures was published separately [Ye *et al.* (1992a)]. This later work involved experimental determinations of the speed of sound for mixtures at various concentrations of methane and *n*-hexadecane, and also of carbon dioxide and *n*-hexadecane, forming particularly asymmetric mixtures. Experimentation also included moderately asymmetric mixtures of *n*-hexane and *n*-hexadecane. Various mixing rules were tested and, in particular, rules were tested for pseudocritical parameters by combination of critical properties of components. Ye *et al.* (1991) discussed results for binary mixtures of methane with hexadecane and carbon dioxide with hexadecane.

Daridon, Lagourette, and Xans (1994) devised an experimental system based on pulse-echo ultrasonics for the determination of density, ultrasonic speed, and phase equilibria over a wide range of pressures. This system was particularly well suited for investigating the type of high pressure, high temperature conditions observed in deep oil reservoirs. Results were presented for experiments conducted on a binary mixture of nitrogen and octane between its saturation pressure and 100 MPa at temperatures ranging between 30 and 100 °C. Related work in studying sound speed in liquid and gas mixtures, including in particular a study of the speed of sound in *n*-octane, was detailed in Daridon (1994). In a subsequent series of studies, a variety of liquids of interest to the petroleum industry was studied. Daridon *et al.* (1996) presented ultrasonic speed measurements in a hyperbaric reservoir fluid between its saturation pressure and 120 MPa, in a range from 40 to 180 °C. Daridon, Lagourette, and Labes (1996) presented speed of sound measurements on three mixtures of the ternary system methane+carbon dioxide+normal hexadecane in pressure ranges of 12–70 MPa, and in temperature ranges from 40 to 120 °C. These measurements were used to evaluate the isothermal and isentropic compressibilities up to 70 MPa from lower pressure density data.

Daridon and Lagourette (1996) presented results for ultrasonic speeds in a methane+propane+octane ternary mixture up to 100 MPa and at temperatures from 20 to 120 °C, which allowed evaluation of vapor–liquid phase boundary, and density and isothermal compressibility up to 100 MPa from lower pressure data.

Daridon, Lagourette, and Xans (1998) detailed results from experiments involving the measurement of ultrasonic speed of sound in pressure ranges of 0.1–150 MPa at temperatures ranging from 20 to 100 °C in real and a synthetic heavy cut (petroleum distillation fraction). The sound speed measurements were then used to generate density data by integrating the inverse of the square sound speed with respect to pressure. The isentropic compressibility could then be deduced from the simultaneous knowledge of ultrasonic speed and density. Finally, the acoustic measurements were used for the indirect determination of the isothermal compressibility.

In another recent paper [Daridon, Lagourette, Lagourette (1998d)] isentropic and isothermal compressibilities were obtained from ultrasonic speed measurements on two synthetic systems which were representative of distillation cuts with high bubble points ( $T=247$  °C and  $T=300$  °C, respectively). The first system (with composition expressed in mass fraction)  $0.40\text{C}_{13}\text{H}_{28}+0.35\text{C}_{13}\text{H}_{26}+0.25\text{C}_{13}\text{H}_{20}$ , was investigated at (absolute) pressures ranging from 0.1 to 150 MPa in temperatures ranging from 20 to 100 °C. The second system,  $0.40\text{C}_{17}\text{H}_{36}+0.35\text{C}_{16}\text{H}_{32}+0.25\text{C}_{16}\text{H}_{26}$ , was investigated at pressures up to 100 MPa and at temperatures ranging from 20 to 100 °C.

Yet another paper in this prolific series [Daridon *et al.* (1998b)] studied the speed of sound in liquid *n*-hexane from 20 to 100 °C at pressures up to 150 MPa. The data were then

used to evaluate isentropic and isothermal compressibilities. The speed-of-sound measurements, as well as the related compressibility coefficients, compared well with previous studies. Daridon *et al.* (1998e) studied ultrasonic speed measurements under pressure on three reservoir fluids highly dissimilar in both composition and nature. The most appropriate equation of state–mixing rule combinations were identified for predicting thermophysical properties of these fluids. Additionally, the influence of the number of cuts and the mode of grouping on speed of sound calculations was examined. A comparative analysis between measurement and theory showed that the Lee–Kesler model was very satisfactory at even the highest pressures measured: 120 MPa. Daridon *et al.* (1998a) reported speed of sound measurements for three ternary or quaternary synthetic systems over temperatures ranging between 20 and 100 °C, and at pressures ranging up to 150 MPa.

Finally, Goold, Bennell and Jones (1996) published a study on the effect of pressure and temperature on sound speed measurements in spermaceti oil. Pressure ranges—from 0.1 to 9.1 MPa—simulated those likely to be experienced by a sperm whale during a dive to 900 m. The speed of sound was found to increase linearly with increasing pressure, and to decrease nonlinearly with increasing temperature. There was no sudden change in sound speed as the oil changed phase from liquid to solid. A least-squares multiple polynomial regression analysis produced a practical equation for the prediction of sound speed in spermaceti oil as a function of temperature and pressure

## 8. Brillouin Scattering Experiments (1980s through Present)

The theory of Brillouin scattering from condensed matter is available in several textbooks and review articles. [Berne and Pecora (1976); Chu (1974); Boon and Yip (1976); Fluery and Boon (1973); Dil (1982)]. In essence, from the analysis of the Rayleigh–Brillouin spectra of scattered light one can determine the following quantity:

$$\text{Brillouin shift} = \Delta \nu_B = \pm \frac{2n_l \nu_s}{\lambda_0} \sin(\theta/2),$$

where  $\nu_s$  is the sound speed,  $\theta$  is the scattering angle,  $\lambda_0$  is the wavelength of the incident light, and  $n_l$  is the index of refraction of the medium. Determination of the speed of sound,  $\nu_s(P)$ , from the above equation is not a simple matter, since it requires knowledge of  $n_l(P, T)$ . This latter quantity is itself formidable to find.

However, when the incident light beam and the detected scattered light beam are optically arranged symmetric to the scattering volume, the above equation reduces to

$$\Delta \nu_B = \pm \frac{\sqrt{2}}{\lambda_0} \nu_s.$$

Through this relationship, the sound speed in a liquid can be readily determined experimentally from Brillouin shifts.

In one of the earliest works in Brillouin scattering, Stith *et al.* (1974) measured hypersound speeds in carbon disulfide, acetone, and benzene at 27 °C with pressure up to 100 MPa. For this range the hypersonic speeds in carbon disulfide and acetone increased linearly with pressure. Similar results were obtained for benzene below 41 MPa, but the slope tapered off at higher pressures due to vibrational relaxation. This early study was furthered by the 1983 work of Asenbaum and Hochheimer [Asenbaum and Hochheimer (1983)], who studied the hypersound velocity and energy relaxation time of benzene as a function of pressure up to 130 MPa, with temperatures from 25 to 70 °C. The results for hypersound velocity were in agreement with the earlier work of Medina and O'Shea (1977), while the data for relaxation time was in good agreement with Einwohner and Adler's model (1968) for binary collision.

In the work of Shimizu, Sasaki, and Ishidate (1987), Brillouin scattering was measured at room temperature in liquid and solid CS<sub>2</sub> in a diamond anvil cell up to 7000 MPa. In the liquid phase, the acoustic velocity and the refractive index were determined as a function: the equation of state was determined to be  $\rho = 0.206P^{0.40} + 1.144$  (100 MPa  $\leq P \leq$  1300 MPa) with density  $\rho$  in g/cm<sup>3</sup> and the pressure  $P$  in kbar. This work was followed by that of Brown *et al.* (1988), which investigated the speed of sound and equations of state for methanol and ethanol in a diamond-anvil cell at pressures up to 6.8 GPa.

In a series of studies initiated at the University of Oslo in the late 1980s, Himadri Bohidar examined the pressure dependence of sound velocity for a variety of liquids. In Bohidar *et al.* (1987), experimental results were least-squares fitted to a theoretical model for sound speed as a function of pressure, based on a derivation from the modified Tait equation:

$$v_s(P) = A_0 + A_1P + A_2P^2,$$

where  $A_0 = v_0$  (the sound velocity at 1 bar),  $A_1/A_0 = (\alpha - \beta_{T0})/2$ , and  $A_2/A_0 = \frac{1}{4}[(n + \frac{1}{2})\beta_{T0}^2 - \alpha\beta_{T0}]$ . (In the latter expressions,  $\beta_{T0}$  was the isothermal compressibility at 100 kPa,  $n$  was the index of refraction of the liquid at 100 kPa, and  $\alpha$  the normalized first pressure derivative of the bulk modulus.)

In a 1988 study [Bohidar (1988a)], the sound velocity was found to increase by about 35% in carbon tetrachloride, acetic acid, isopropyl alcohol, and ethanol as the pressure was raised from 1 to approximately 82.5 MPa at a temperature of 20 °C. For benzene, hexane, methanol, and toluene, the sound speed increased by about 20% over that range. The maximum increase was 40%, for acetone. The smallest increase was in water, slightly less than 20%. No specific trend with respect to the dipole nature of the liquids (associated or nonassociated) was observed. For all liquids, the sound speed increased nonlinearly with applied pressure. In Bohidar's next study (1988b), the Brillouin scattering technique was used to measure the pressure dependence of sound speed in model oil samples (each containing 5-hydrocarbon liquids) at 20 °C. Experimental results were reported on two

blends of model oil, each containing a mixture of *n*-heptane, *n*-tetradecane, cyclohexane, benzene, and toluene in different volume fractions. Based upon the difference in adiabatic compressibility between the two oils, the increase in the sound velocity with pressure (which took a slightly different form in each of the model oils) was found to be due to the increase in the adiabatic bulk modulus of these oil blends. There were no previous experimental results with which these findings could have been compared.

Later studies included the pressure dependence of the speed of sound in binary liquids: acetic acid+ethanol, *n*-propanol+hexane, benzene+acetone, *n*-propanol+toluene, hexane+CCl<sub>4</sub>, and methanol+water [Bohidar (1989b)]. Bohidar [(1989a), (1989b)] studied the pressure dependence of hypersonic impedance ( $Z_p$ ) and specific heat ratio ( $\gamma$ ) for ten organic liquids, six binary liquids, and two model oils. The study, conducted at 20 °C with pressure from 0.1 to 80 MPa, found large changes in both  $Z_p$  and  $\gamma$ ; there was no direct correlation found with respect to the associative nature of the liquids. Surprisingly, Bohidar's study of binary liquids resulted in nearly identical percentage increases of the hypersonic impedance with pressure, regardless of combination or percentage mixture. Very dilute solutions of macromolecules were also studied, including bovine serum albumin, insulin, and polystyrene [Bohidar (1989c)].

Changing focus to other researchers of the time, Lee *et al.* (1990) studied the LA phonon velocity in methanol at pressures up to 8.4 GPa. The pressure dependence of the LA phonon lifetimes was obtained from the linewidth of the measured Brillouin peaks. From backscattering experiments, the normalized phonon attenuation was found to be a decreasing function of pressure.

Nakamura *et al.* (1991) used the Brillouin scattering method to determine sound velocities in lubricating oils at pressures above 1 GPa. In the pressure range of this study fluids could no longer be modeled as Newtonian. For lubricants with long flexible molecular chain structures, the data coincided with Dowson's equation up to 1 GPa, but the relative density was increased more than expected beyond 1 GPa. Nakamura *et al.* (1994) focused on paraffinic oil and naphthenic oil at pressures above 1 GPa using a diamond anvil cell with a Brillouin scattering spectra of both 90° and 180°. Another diamond-anvil cell, similar to that of Bohidar, was used by Nakamura, Fujishiro and Tamura (1995a) to study sound speed via Brillouin scattering in alcohols, hydrocarbons, and synthetic lubricants under pressures up to 6000 MPa. The sound speed versus pressure relationship for methanol obtained up to the pressure of 6000 MPa was very close to existing data, with less dispersion. Normal heptane and methylcyclohexane showed a discontinuity of sound speed at around 1500 MPa, which was the result of crystallization of the sample liquids. With *n*-heptane, sound speeds of both longitudinal and transverse mode were obtained. Pressure-sound speed relationships of naphthenic oils were expressed by two lines intersecting at about 1000 MPa, which agrees with the glass transition point of the existing data. In a later study [Nakamura *et al.* (1995b)], Brillouin



scattering spectra and their transverse modes were measured for paraffinic and naphthenic synthetic lubricants.

Bak and Sooryakuma (1994) published a Brillouin scattering study involving the pressure dependence of the speed of sound in a methanol–ethanol solution. Pressures up to 8.1 GPa were studied: the results agreed well with estimates experimentally determined by Brown *et al.* (1988) and implicitly determined by Polian *et al.* (1982).

Shimizu *et al.* (1996) studied the acoustic velocities independent direction, refractive index, elastic constants, and elastic anisotropy of liquid and solid methane at pressures up to 5 GPa. Along a similar vein, Sasaki, Nakashima, and Shimizu (1996) determined the three elastic constants in the orientationally disordered solid phase of methane. The velocity of the slow transverse acoustic mode in the  $\langle 110 \rangle$  direction was found to be insensitive to pressure as compared with other velocities, which led to the tentative conclusion that the rotation–translation coupling has a strong pressure dependence.

## 9. Thermodynamic Methods of $B/A$ Measurement

The nonlinearity parameter  $B/A$  can be expressed through thermodynamic expansion as the sum of two terms [Beyer (1960)]: a pressure derivative term  $(B/A)'$ , which is the dominant part of the expression, and a temperature derivative term  $(B/A)''$

$$\frac{B}{A} = \rho_0 c_0 \left( \frac{\partial c}{\partial p} \right)_T + \frac{\beta T \rho_0}{c_p} \left( \frac{\partial c}{\partial T} \right)_p = \left( \frac{B'}{A} \right) + \left( \frac{B''}{A} \right).$$

Here,  $\rho_0$  is the undisturbed density,  $c_0$  is the speed of sound at specified conditions,  $(\partial c/\partial p)_T$  is the change of sound speed with pressure at constant temperature,  $\beta$  is the volume coefficient of thermal expansion,  $T$  is the absolute temperature,  $c_p$  is the specific heat at constant pressure, and  $(\partial c/\partial T)_p$  is the change of sound speed with temperature at constant pressure. The method of measurement based on this equation was first suggested by Coppens *et al.* (1965) for use with liquids.

Of interest to this review, the  $(\partial c/\partial p)_T$  term has been measured in a variety of liquids pursuant to the calculation of the  $B/A$  parameter. It is regrettable that, although measurements are taken of sound speed as a function of pressure in many of these experiments, the results are rarely tabulated as such. Instead, either a single  $(\partial c/\partial p)_T$  term, or the final calculated  $B/A$  value itself, is published from experimentally obtained results. As such, only an introduction to the broad range of  $B/A$  parameter literature is provided here.

A good representative work in this area is that of Sarvazyan, Chalikian, and Dunn (1990). In this study, a precision ultrasonic velocimeter and a new differential method of calculation of specific concentration increments were employed to study the nonlinear acoustic properties of aqueous solutions of ten amino acids and six proteins. Values of  $\Delta(\partial c/\partial p)_T$  were determined by measuring  $c$  (the speed of

sound) at 0.1, 5, 10, 15, and 20 MPa. The measurements of sound speed in the solutions at the five pressures allowed determination of the dependence of the sound speed on pressure with “high accuracy” and calculation of the initial slope  $\Delta(\partial c/\partial p)_T$ . These explicit results were not provided in the published findings, since the focus of the paper was the strong influence of the character of the solute–solvent interaction on the  $B/A$  parameter.

In an example involving the  $B/A'$  parameter, earlier work involving ultrasonic speed and  $B/A'$  for 1-propanol were furthered by Hagelberg (1970). In this study, conducted at 30 °C with a pressure range to 980 MPa, the speed increased and the  $B/A'$  parameter decreased as functions of pressure. The results for ultrasonic speed corroborated the earlier work of Wilson and Bradley.

Zhang and Dunn (1991) pressurized samples of various liquids, including distilled water, 25% dextrose, and ethylene glycol, to 10 MPa. The speed of sound was measured, and then the pressure vessel was allowed to rapidly ( $\sim 1$  s) depressurize to approximate an adiabatic process. The change in speed so determined was used to calculate the  $B/A$  values, which were published in tabulated form. Experimentally determined sound speeds as a function of pressure and calculated values for  $(\partial c/\partial p)_T$  were not provided in the published results.

An interesting method using an acoustic interferometer was used to measure the small changes in sound speed that accompany a rapid hydrostatic pressure change of between 1 and 2 atm was developed by Everbach and Apfel (1995). Average accuracies of 0.85% were found to be attainable with this method. The acoustic nonlinearity parameter  $B/A$  of several aqueous buffers, protein solutions, lipid oils, and emulsions was reported, with some intermediate values (e.g., density and sound speed) reported as a function of temperature, but not of pressure.

## 10. Conclusions and Further Work

The study of acoustic parameters as a function of pressure has found great and continually increasing use in providing for convenient and highly accurate methods of obtaining parameters such as compressibility and specific heat. Data so obtained are relevant to a broad spectrum of disciplines, including petroleum and mechanical engineering, oceanography, medicine, tribology, and basic physics and chemistry.

Many studies of ultrasonic speed and absorption as a function of pressure, particularly those prior to roughly 1970, suffered from poor theoretical understanding of liquids. (Indeed, although theoretical knowledge is improving, there is still a problem in this area.) Experimental values received from the mid 1950s on could be profitably reanalyzed in light of a more modern understanding of liquids. As the companion review [Oakley *et al.* (2003)] explains, even today there is a lack of a unified theory for experimental results involving the speed of sound in organic liquids.

Reviews of the various types of instrumentation used in the studies mentioned in this paper would be very valuable.

Such a study could point out the advantages and disadvantages of the many different devices and techniques currently (and previously) in use, with an aim of clarifying the devices and techniques that might be appropriate to different pressure regimes and different liquids under study. (The single such review in the literature [Takagi (1994a)], is in Japanese.)

In many common liquids, ultrasonic parameters such as sound speed and absorption are not exceptionally sensitive to the absolute hydrostatic pressure of a liquid. Sound speed generally increases with increasing pressure, while absorption decreases with increasing pressure. Relaxation frequency however, can increase, decrease, or remain unchanged as a function of pressure depending upon the relaxational mechanism. It should be noted that many of the studies cited in this review were conducted at isolated ultrasonic frequencies between 2 and 10 MHz. It may be appropriate for some substances to conduct further studies at differing frequencies: it would be very interesting in many cases to know the speed of sound, for example, as both a function of pressure and a function of frequency.

Many substances, particularly substances common in biological processes, have not been investigated [MacDonald (1997)]. Human platelets, for example, appear to “detect” hydrostatic pressures of 26 kPa: such a pressure enhances the release of platelet factor 4 and betathromboglobulin, and increases the formation of malondialdehyde [Torsellini (1984)]. These supremely pressure sensitive substances indicate that perhaps as common a substance as blood itself may display very interesting acoustical properties as a function of pressure.

Along these lines, the determination of the acoustic non-linearity parameter ( $B/A$ ), which is frequently determined in connection with biological materials, may hold relevant and useful results. It would be of great value to see tabulated results for sound speed as a function of pressure provided in future studies on the subject.

The study of acoustical parameters as a function of pressure is a fundamentally important topic that has led to im-

portant insights in the characterization of liquids. It is also a broad and sweeping subject that covers a startling variety of materials, methods, and insights. It is hoped that this review will provide a coherent framework for this complex subject area from which even more fruitful future studies may grow.

## 11. List of Terms

$$\beta = \frac{1}{v} \left( \frac{\partial v}{\partial t} \right)_p = - \frac{1}{\rho} \left( \frac{\partial \rho}{\partial T} \right)_p = \text{coefficient of thermal expansion,}$$

$$\kappa_T = - \frac{1}{v} \left( \frac{\partial v}{\partial P} \right)_T = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial P} \right)_T = \text{isothermal compressibility factor,}$$

$$\kappa_S = - \frac{1}{v} \left( \frac{\partial v}{\partial P} \right)_S = \frac{1}{\rho} \left( \frac{\partial \rho}{\partial P} \right)_S = \text{adiabatic compressibility factor (bulk modulus for adiabatic compression),}$$

$\rho$  = density,

$\gamma$  =  $C_P/C_V$ ,

$C_P$  = specific heat at constant pressure, and

$C_V$  = specific heat at constant volume.

## 12. Acknowledgments

The comments and recommendations of Dr. J.P.M. Trusler, Dr. Dipen Sinha, Dr. Toshiharu Takagi, Dr. Jean luc Daridon, Dr. B. Lagourette, and Dr. Roman Dembinski are deeply appreciated. Thanks are also given for the assistance of Michael Latcha, Jeffrey Peters, and Kris Allen. The support of the DeVlieg Foundation, the NASA/Michigan Space Grant Consortium, and the Haas Fund of Mt. Sinai Hospital in Cleveland is gratefully acknowledged. This work was supported in part through National Science Foundation Grant No. 9977859 and through a grant from the NASA/Michigan Space Consortium.

TABLE 1. Compilation of ultrasonic investigations as a function of pressure in organic liquids, including investigator, focus of investigators, pressure and temperature ranges of investigators' experimental work, and brief comments as to technique used by investigator(s) in obtaining experimental results (experimental frequencies noted where available)

Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
Acetaldehyde (CH <sub>3</sub> CHO)	Eden and Richardson (1960) sound speed, attenuation	0.1–55 MPa 8–15 °C	ultrasonic pulse (3 MHz)
Acetic acid (CH <sub>3</sub> COOH)	Litovitz and Carnevale (1958) absorption, relaxation frequency, sound speed	155 MPa (only) 50 °C	pulse echo (2.4 MHz)
	Bohidar (1988a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Acetic acid+ethanol (CH <sub>3</sub> CO <sub>2</sub> H+CH <sub>3</sub> CH <sub>2</sub> OH)	Bohidar (1988b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Acetone (CH <sub>3</sub> COCH <sub>3</sub> )	Eden and Richardson (1960) sound speed, attenuation	0.1–55 MPa 20 °C, 30 °C, and 40 °C	ultrasonic pulse (3 MHz)
	Stith <i>et al.</i> (1974) sound speed	0.1–100 MPa 2 °C	Brillouin scattering
	Ismagilov and Ermakov (1982) sound speed	0.1–2.5 MPa 114–177 °C	pulse echo (2.5 MHz)
	Bohidar (1988a) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Acetone+benzene (CH <sub>3</sub> COCH <sub>3</sub> +C <sub>6</sub> H <sub>6</sub> )	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Albumin (bovine serum, in dilute solution)	Bohidar (1989c) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
Amyl propionate (C <sub>2</sub> H <sub>5</sub> CO <sub>2</sub> C <sub>5</sub> H <sub>11</sub> )	Guseinov and Klimova (1983) sound speed	0.1–50 MPa –63–97 °C	pulse echo
Aniline (C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> )	Swanson (1934) sound speed	0.1–28.2 MPa 23.7 °C	interferometer (197.7 kHz)
	Takagi (1976) sound speed	0.1–210 MPa 10–60 °C	ultrasonic pulse (1 MHz)
Aniline+benzene (C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> +C <sub>6</sub> H <sub>6</sub> )	Takagi (1980a) sound speed	0.1–207 MPa 25 °C	pulse echo (1 MHz)
Aniline+chlorobenzene (C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> +C <sub>6</sub> H <sub>5</sub> Cl)	Takagi (1980a) sound speed	0.1–207 MPa 25 °C	pulse echo (1 MHz)
Aniline+nitrobenzene (C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> +C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> )	Takagi (1978b) sound speed	0.1–210 MPa 30 °C	pulse echo (1 MHz)
Aniline+toluene (C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> +C <sub>6</sub> H <sub>5</sub> CH <sub>3</sub> )	Takagi and Teranishi (1985c) sound speed	0.1–180 MPa 30 °C	ultrasonic pulse (1 MHz)



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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
Aroclor 1254 (58% pentachlorobiphenyl and 42% other chlorinated biphenyls)	Hutton <i>et al.</i> (1978) absorption, sound speed, viscoelasticity	0.1–260 MPa –87 to 90 °C	ultrasonic pulse (5–78 MHz)
Benzene (C <sub>6</sub> H <sub>6</sub> )	Swanson (1934) sound speed	0.1–34.3 MPa 25.5 °C	interferometer (193.7 kHz)
	Biquard (1938) sound speed	6.6–54 MPa 18.5–20 °C	diffraction of light by ultrasound (10 MHz)
	Biquard (1939) sound speed	6.6–54 MPa 18.5–20 °C	diffraction of light by ultrasound (10 MHz)
	Mifsud and Nolle (1956) sound speed, absorption, relaxation frequency	0.1–138 MPa 25 and 50 °C	pulse echo (5.0 MHz)
	Richardson and Tait (1957) sound speed, absorption	0.1–68.9 MPa 19–40 °C	ultrasonic pulse (3 MHz)
	Makita and Takagi (1968) sound speed	0.1–253 MPa 10 and 70 °C	ultrasonic pulse (1 MHz)
	Collings and McLaughlin (1970) viscosity	0.1–17.2 MPa 30–50 °C	torsional vibrating quartz (39 kHz)
	Stith <i>et al.</i> (1974) sound speed	0.1–100 MPa 27 °C	Brillouin scattering
	Otpushchennikov <i>et al.</i> (1974a) sound speed	0.1–100 MPa 50–90 °C	ultrasonic pulse (1 and 3.5 MHz)
	Medina and O'Shea (1977) sound speed	0.1–328 MPa 25–75 °C	Brillouin scattering
	Bobik (1978) sound speed	0.1–62 MPa, 10–190 °C	pulse echo (2 MHz)
	Pevnyi and Otpushchennikov (1980a) sound speed	5.1–51 MPa 52 °C	ultrasonic pulse (1 and 10 MHz)
	Ismagilov and Ermakov (1982) sound speed	0.1–2.5 MPa 120–194 °C	pulse echo (2.5 MHz)
	Asenbaum and Hochheimer (1983) sound speed	0.1–130 MPa 25–70 °C	Brillouin scattering
	Takagi and Teranishi (1984c) sound speed	0.1–160 MPa 20, 25, and 30 °C	pulse echo (2 MHz)
	Melikhov (1985) sound speed	0.1–300 MPa 30–120 °C	pulse echo (4 MHz)
<i>m</i> -bis ( <i>m</i> -phenoxy phenoxy) benzene (C <sub>30</sub> H <sub>22</sub> O <sub>4</sub> )	Sun <i>et al.</i> (1987) sound speed	0.1–170 MPa 10–50 °C	pulse echo (2 MHz)
	Takagi and Teranishi (1987a) sound speed	0.1–200 MPa 10–50 °C	pulse echo (2 MHz)
	Bohidar (1988a) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
	Takagim (1994) sound speed	0.1–200 MPa 10–50 °C	pulse echo (2 MHz)
	Bezot <i>et al.</i> (1986) viscoelastic parameters	0.1–300 MPa 20–60 °C	light scattering and ultrasonic technique (1 MHz)

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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
Benzene+acetone (C <sub>6</sub> H <sub>6</sub> + CH <sub>3</sub> COCH <sub>3</sub> )	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Benzene+aniline (C <sub>6</sub> H <sub>6</sub> + C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> )	Takagi (1980a) sound speed	0.1–207 MPa 25 °C	pulse echo (1 MHz)
Benzene+bromobenzene (C <sub>6</sub> H <sub>6</sub> + C <sub>6</sub> H <sub>5</sub> Br)	Takagi and Teranishi (1982a) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
Benzene+chlorobenzene (C <sub>6</sub> H <sub>6</sub> + C <sub>6</sub> H <sub>5</sub> Cl)	Takagi and Teranishi (1982a) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
Benzene+cyclohexane (C <sub>6</sub> H <sub>6</sub> + C <sub>6</sub> H <sub>12</sub> )	Takagi and Teranishi (1980b) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
Benzene+nitrobenzene (C <sub>6</sub> H <sub>6</sub> + C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> )	Takagi and Teranishi (1982b) sound speed	0.1–200 MPa at 30 °C 30 MPa at 20–40 °C	pulse echo (1 MHz)
Benzene+toluene (C <sub>6</sub> H <sub>6</sub> + C <sub>6</sub> H <sub>5</sub> CH <sub>3</sub> )	Takagi (1978c) sound speed	0.1–200 MPa 20, 30, and 40 °C	ultrasonic pulse (1 MHz)
Benzene+an isomeric xylene (C <sub>6</sub> H <sub>6</sub> + C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub> )	Takagi (1981) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
Benzene+ <i>o</i> -xylene (C <sub>6</sub> H <sub>6</sub> + C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub> )	Takagi (1978c) sound speed	0.1–200 MPa 20, 30, and 40 °C	ultrasonic pulse (1 MHz)
Benzonitrile+nitrobenzene (C <sub>7</sub> H <sub>5</sub> N+ C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> )	Takagi and Teranishi (1988a) sound speed	0.1–100 MPa 25 and 30 °C	pulse echo (2 MHz)
Bromobenzene (C <sub>6</sub> H <sub>5</sub> Br)	Eden and Richardson (1960) sound speed, attenuation	0.1–55 MPa 22 °C	ultrasonic pulse (3 MHz)
Bromobenzene+benzene (C <sub>6</sub> H <sub>5</sub> Br+ C <sub>6</sub> H <sub>6</sub> )	Takagi and Teranishi (1982a) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
Bromobenzene+chlorobenzene (C <sub>6</sub> H <sub>5</sub> Br+ C <sub>6</sub> H <sub>5</sub> Cl)	Takagi and Teranishi (1984b) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
<i>n</i> -Butane (C <sub>4</sub> H <sub>10</sub> )	Niepmann (1984) sound speed	coexistence line to 60 MPa –73 to 102 °C	pulse echo (2 MHz)
<i>iso</i> -Butanol (CH <sub>3</sub> (CH <sub>2</sub> ) <sub>2</sub> CH <sub>2</sub> OH)	Shoitov and Otpushchennikov (1968) sound speed	0.1–50 MPa 50–110 °C	pulse echo (1 MHz)
<i>n</i> -Butanol (CH <sub>3</sub> (CH <sub>2</sub> ) <sub>2</sub> CH <sub>2</sub> OH)	Carnevale and Litovitz (1955) absorption, sound speed	0.1–196 MPa 0–45 °C	pulse echo (25 MHz)
	Wilson and Bradley (1964) sound speed	0.1–96 MPa 0–60 °C	ultrasonic pulse (5 MHz)
	Shoitov and Otpushchennikov (1968) sound speed	0.1–50 MPa 50–110 °C	pulse echo (1 MHz)
	Hawley <i>et al.</i> (1970) sound speed, absorption	0.1–489 MPa 30 °C	pulse echo (22 MHz region)
	Sysoev and Otpushchennikov (1976a) sound speed	0.1–860 MPa 30 °C	pulse echo (4 MHz)

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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
	Sysoev <i>et al.</i> (1976) sound speed	0.1–911 MPa 17.2 and 150 °C	ultrasonic pulse
	Sysoev <i>et al.</i> (1976) sound speed	0.1–861 MPa 20–150 °C	pulse echo
	Sysoev and Otpuschennikov (1977) sound speed	0.1–861 MPa 17–150 °C	pulse echo (4 MHz)
	Pevnyi and Otpuschennikov (1980a) sound speed	0.1–709 MPa 20–250 °C	ultrasonic pulse (1 and 10 MHz)
<i>n</i> -Butyl acetate (CH <sub>3</sub> COOCH <sub>2</sub> CH(CH <sub>3</sub> ) <sub>2</sub> )	Nomura <i>et al.</i> (1971) sound speed, <i>B/A</i> parameter	0.1–30.3 MPa 5–35 °C	ultrasonic interferometer (4 MHz)
Butylbenzene (CH <sub>3</sub> (CH <sub>2</sub> ) <sub>3</sub> C <sub>6</sub> H <sub>5</sub> )	Makhno <i>et al.</i> (1985) sound speed	0.1–245 MPa 40–180 °C	pulse echo (2 MHz)
Butylphenyl ether (C <sub>4</sub> H <sub>9</sub> OC <sub>6</sub> H <sub>5</sub> )	Pevnyi and Otpuschennikov (1981) sound speed	0.1–800 MPa 20–250 °C	pulse echo (2 MHz)
Carbon dioxide (CO <sub>2</sub> ) (liquid)	Richardson and Tait (1957) sound speed, absorption	6.9–20.7 MPa 19 °C	ultrasonic pulse (1 MHz)
Carbon dioxide + <i>n</i> -hexadecane (CO <sub>2</sub> + C <sub>16</sub> H <sub>34</sub> )	Ye <i>et al.</i> (1991) sound speed	5–50 MPa 20–60 °C	pulse echo (5 MHz)
	Ye <i>et al.</i> (1992a) sound speed	0.1–70 MPa 20–60 °C	pulse echo (5 MHz)
Carbon dioxide (gas) + <i>n</i> -hexadecane (liquid) + methane (gas) (CO <sub>2</sub> + C <sub>16</sub> H <sub>34</sub> + CH <sub>4</sub> )	Daridon <i>et al.</i> (1996) sound speed	12–70 MPa 40–120 °C	pulse echo (2 MHz)
Carbon disulfide (CS <sub>2</sub> )	Swanson (1934) sound speed	0.1–21.4 MPa 23.5 °C	interferometer (193.9 kHz)
	Mifsud and Nolle (1956) sound speed, absorption, relaxation frequency	0.1–138 MPa 25 and 50 °C	pulse echo (2.0 MHz)
	Litovitz <i>et al.</i> (1957); results also referred to in Litovitz (1957), and Litovitz and Carnevale (1958); absorption, relaxation frequency, sound speed	0.1–98 MPa –29 °C	pulse echo (15–75 MHz)
	Stith <i>et al.</i> (1974) sound speed	0.1–100 MPa 27 °C	Brillouin scattering
Carbon tetrachloride (CCl <sub>4</sub> )	Shimizu <i>et al.</i> (1987) sound speed	0.1–7000 MPa 27 °C	Brillouin scattering
	Swanson (1934) sound speed	0.1–21.2 MPa 23.0 °C	interferometer (197.8 kHz)
	Biquard (1938) sound speed	25.7–56.0 MPa 18 °C	diffraction of light by ultrasound (10 MHz)
	Biquard (1939) sound speed	25.7–62.1 MPa 18 °C	diffraction of light by ultrasound (10 and 6.92 MHz)
	Mifsud and Nolle (1956) sound speed, absorption, relaxation frequency	0.1–138 MPa 25 and 50 °C	pulse echo (4.85 and 10 MHz)



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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
	McSkimin (1957) sound speed, absorption	0.1–145 MPa 5.6–50 °C	ultrasonic pulse (20 MHz)
	Richardson and Tait (1957) sound speed, absorption	0.1–68.9 MPa 15.5, 25, and 40 °C	ultrasonic pulse (3 MHz)
	Makita and Takagi (1968) sound speed	0.1–253 MPa 10 and 70 °C	ultrasonic pulse (1 MHz)
	Hawley <i>et al.</i> (1970) sound speed, absorption	0.1–288 MPa 30 and 75 °C	pulse echo (13.4 MHz region)
	Collings and McLaughlin (1970) viscosity	0.1–17.2 MPa 30–50 °C	torsional vibrating quartz (39 kHz)
	Bobik <i>et al.</i> (1979) sound speed	coexistence region to 62 MPa –8 to 162 °C	pulse echo (2 MHz)
	Sysoev and Otpuschennikov (1979) sound speed	0.1–506 MPa 20–180 °C	ultrasonic pulse (5 MHz)
	Lainez <i>et al.</i> (1987) sound speed	0.1–55 MPa 56–136 °C	pulse echo (3 MHz)
	Bohidar (1987) sound speed	0.1–80 MPa 50.5 °C	Brillouin scattering
Carbon tetra-chloride + hexane (CCl <sub>4</sub> + C <sub>6</sub> H <sub>14</sub> )	Bohidar (1988a) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) sound speed	0.1–80 MPa 20 °C	Brillouin scattering
Chlorobenzene (C <sub>6</sub> H <sub>5</sub> Cl)	Eden and Richardson (1960) sound speed, attenuation	0.1–55 MPa 22 °C	ultrasonic pulse (3 MHz)
	Takagi (1975) sound speed	0.1–210 MPa 10–60 °C	ultrasonic pulse (1 MHz)
Chlorobenzene + aniline (C <sub>6</sub> H <sub>5</sub> Cl + C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> )	Takagi (1980a) sound speed	0.1–207 MPa 25 °C	pulse echo (1 MHz)
Chlorobenzene + benzene (C <sub>6</sub> H <sub>5</sub> Cl + C <sub>6</sub> H <sub>6</sub> )	Takagi and Teranishi (1982a) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
Chlorobenzene + bromobenzene (C <sub>6</sub> H <sub>5</sub> Cl + C <sub>6</sub> H <sub>5</sub> Br)	Takagi and Teranishi (1984b) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
Chlorobenzene + nitrobenzene (C <sub>6</sub> H <sub>5</sub> Cl + C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> )	Takagi and Teranishi (1984a) sound speed	0.1–200 MPa 20–40 °C	pulse echo (1 MHz)
Chlorodifluoro-methane (CHClF <sub>2</sub> )	Niepmann <i>et al.</i> (1987) sound speed	coexistence line to 60 MPa –73 to 147 °C	pulse echo (2 MHz)
Chloroform (CHCl <sub>3</sub> )	Swanson (1934) sound speed	0.1–20.7 MPa 22.7 °C	interferometer (196.5 kHz)
Cyclohexane (C <sub>6</sub> H <sub>12</sub> )	Eden and Richardson (1960) sound speed, attenuation	0.1–28 MPa 19 °C	ultrasonic pulse (3 MHz)
	Collings and McLaughlin (1970) viscosity	0.1–7.8 MPa 30–50 °C	torsional vibrating quartz (39 kHz)

TABLE 1. Compilation of ultrasonic investigations as a function of pressure in organic liquids, including investigator, focus of investigators, pressure and temperature ranges of investigators' experimental work, and brief comments as to technique used by investigator(s) in obtaining experimental results (experimental frequencies noted where available)—Continued

Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
	Takagi (1976) sound speed	0.1–210 MPa 10–60 °C	ultrasonic pulse (1 MHz)
	Melikhov (1985) sound speed	0.1–300 MPa 30–150 °C	pulse echo (4 MHz)
	Sun <i>et al.</i> (1987) sound speed	0.1–80 MPa 10–50 °C	pulse echo (2 MHz)
Cyclohexane + benzene (C <sub>6</sub> H <sub>12</sub> + C <sub>6</sub> H <sub>6</sub> )	Takagi and Teranishi (1980b) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
Decalin C <sub>10</sub> H <sub>18</sub>	Tsydygov and Otpushchennikov (1981) sound speed	0.1–250 MPa 17–177 °C	ultrasonic pulse (1 MHz)
<i>n</i> -Decane (C <sub>10</sub> H <sub>22</sub> )	Badalyan <i>et al.</i> (1970) sound speed	0.1–118 MPa 30–140 °C	ultrasonic pulse (2 MHz)
	Melikhov (1985) sound speed	0.1–300 MPa 30–120 °C	pulse echo (4 MHz)
	Ye <i>et al.</i> (1990) sound speed, attenuation	0.1–60 MPa 30–140 °C	pulse echo (5 MHz)
<i>n</i> -Decane + <i>n</i> -hexane (C <sub>10</sub> H <sub>22</sub> + C <sub>6</sub> H <sub>14</sub> )	Takagi and Teranishi (1985b) sound speed	0.1 MPa up to freezing line or 100 MPa 25 °C	pulse echo (2 MHz)
<i>n</i> -Decane + <i>n</i> -tetradecane (C <sub>10</sub> H <sub>22</sub> + C <sub>14</sub> H <sub>30</sub> )	Takagi and Teranishi (1985b) sound speed	0.1 MPa up to freezing line or 100 MPa 25 °C	pulse echo (2 MHz)
1-Decene (C <sub>10</sub> H <sub>20</sub> )	Badalyan <i>et al.</i> (1971) sound speed	0.1–118 MPa 30–140 °C	ultrasonic pulse (2 MHz)
	Melikhov (1985) sound speed	0.1–300 MPa 31–120 °C	pulse echo (4 MHz)
1-Decanol (C <sub>10</sub> H <sub>22</sub> O)	Sysoev (1977) sound speed	0.1–101 MPa 20–200 °C	pulse echo (5 MHz)
Diallyl ether (C <sub>6</sub> H <sub>10</sub> O)	Pevnyi (1983) sound speed	0.1–800 MPa 50–170 °C	ultrasonic pulse (2 MHz)
Dibutyl ether (C <sub>8</sub> H <sub>18</sub> O)	Pevnyi and Otpuschenikov (1980b) sound speed	0.1–811 MPa 20–170 °C	pulse echo (2 MHz)
Dichloromethane (CH <sub>2</sub> Cl <sub>2</sub> )	Niepmann <i>et al.</i> (1987) sound speed	coexistence line to 60 MPa –73 to 147 °C	pulse echo (2 MHz)
	Takagi (1994a) sound speed	0.1–50 MPa 25–80 °C	pulse echo (2 MHz)
1,1-Dichloro-1-fluoroethane	Takagi and Hongo (1993) sound speed	0.1–50 MPa 10–100 °C	pulse echo (2 MHz)
1,1-Dichloro-2,2,2-trifluoroethane	Takagi (1991) sound speed	0.1–75 MPa 10–100 °C	pulse echo (2 MHz)
1,2-Dichloro-1,2,2-trifluoroethane	Takagi <i>et al.</i> (1992) sound speed	0.1–75 MPa 10–100 °C	pulse echo (2 MHz)

TABLE 1. Compilation of ultrasonic investigations as a function of pressure in organic liquids, including investigator, focus of investigators, pressure and temperature ranges of investigators' experimental work, and brief comments as to technique used by investigator(s) in obtaining experimental results (experimental frequencies noted where available)—Continued

Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
Dichlorotetra-fluoroethane (R114) (CClF <sub>2</sub> –CClF <sub>2</sub> )	Takagi and Teranishi (1986) sound speed	saturated vapor pressure to 50 MPa 10–50 °C	pulse echo (2 MHz)
Diethyl ether (C <sub>4</sub> H <sub>10</sub> O)	Sysoev and Otpuschennikov (1979) sound speed	0.1–506 MPa 17.5–250 °C	ultrasonic pulse (5 MHz)
Di (2-ethylhexyl) phthalate (C <sub>24</sub> H <sub>38</sub> O <sub>4</sub> )	Barlow <i>et al.</i> (1972) shear mechanical resistance	0.1–1400 MPa 30 °C	torsional vibrating quartz (10 and 30 MHz)
	Hutton and Phillips (1972) high frequency, shear modulus	0.1 to 815 MPa –30 to 30 °C	ultrasonic pulse (18–78 MHz)
	Hutton <i>et al.</i> (1978) absorption, sound speed, viscoelasticity	0.1 to 815 MPa –87 to 90 °C	ultrasonic pulse (5–78 MHz)
Di (2-ethylhexyl) phthalate with 1% styrene-ethylene-propylene block copolymer (SEP)	Hutton <i>et al.</i> (1978) absorption, sound speed	0.1–500 MPa –56 to 23 °C	ultrasonic pulse (5–75 MHz)
Difluoromethane (HFC-32) (CH <sub>2</sub> F <sub>2</sub> )	Takagi (1993) sound speed	saturated vapor pressure to 35 MPa –30 to 100 °C	pulse echo (2 MHz)
2,2-Dimethyl-propane (C <sub>5</sub> H <sub>12</sub> )	Lainez <i>et al.</i> (1990) sound speed	0.1–54 MPa –10 to 160 °C	pulse echo (3 MHz)
Dipropyl ether (C <sub>6</sub> H <sub>14</sub> O)	Pevnyi and Otpuschenikov (1980b) sound speed	0.1–811 MPa 20–170 °C	pulse echo (2 MHz)
Di- <i>iso</i> -propyl ether (C <sub>6</sub> H <sub>14</sub> O)	Pevnyi and Otpuschenikov (1980b) sound speed	0.1–811 MPa 20–170 °C	pulse echo (2 MHz)
Dodecane (C <sub>12</sub> H <sub>26</sub> )	Boelhouwer (1967) sound speed	0.1–140 MPa –20 to 200 °C	pulse echo (2 MHz)
	Melikhov (1985) sound speed	0.1–600 MPa 30–160 °C	pulse echo (4 MHz)
<i>n</i> -Dodecane + <i>n</i> -octane (C <sub>12</sub> H <sub>26</sub> + C <sub>8</sub> H <sub>18</sub> )	Takagi and Teranishi (1985b) sound speed	0.1 MPa up to freezing line or 100 MPa 25 °C	pulse echo (2 MHz)
1-Dodecanol (C <sub>12</sub> H <sub>26</sub> O)	Sysoev and Otpuschennikov (1979) sound speed	0.1–507 MPa 30–200 °C	ultrasonic pulse (5 MHz)
Epoxy resin MY 750 (liquid)	Hutton <i>et al.</i> (1978) absorption, sound speed, viscoelasticity	0.1–600 MPa –4 to 70 °C	ultrasonic pulse (5–75 MHz)
Ethanol (C <sub>2</sub> H <sub>5</sub> OH)	Carnevale and Litovitz (1955) sound speed, absorption	0.1–196 MPa 30 °C	pulse echo (45 MHz)
	Eden and Richardson (1960) sound speed, attenuation	0.1–69 MPa 20 °C	ultrasonic pulse (3 MHz)
	Wilson and Bradley (1964) sound speed	0.1–96 MPa 0–60 °C	ultrasonic pulse (5 MHz)
	Hawley <i>et al.</i> (1970) sound speed, absorption	0.1–479 MPa 30 °C	pulse echo (31 MHz region)
	Sysoev <i>et al.</i> (1976) sound speed	0.1–990 MPa 0 and 50 °C	ultrasonic pulse

TABLE 1. Compilation of ultrasonic investigations as a function of pressure in organic liquids, including investigator, focus of investigators, pressure and temperature ranges of investigators' experimental work, and brief comments as to technique used by investigator(s) in obtaining experimental results (experimental frequencies noted where available)—Continued

Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
Ethanol+acetic acid (CH <sub>3</sub> CH <sub>2</sub> OH+CH <sub>3</sub> CO <sub>2</sub> H)	Bohidar (1988a) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Brown <i>et al.</i> (1988) sound speed	0.1–6800 MPa	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
	Fujishiro <i>et al.</i> (1992) sound speed	0.1–6000 MPa 19–23 °C	Brillouin scattering
	Nakamura <i>et al.</i> (1995a) sound speed	0.1–2400 MPa 26 °C	Brillouin scattering
Ethanol+methanol (CH <sub>3</sub> CH <sub>2</sub> OH+CH <sub>3</sub> OH)	Bohidar (1988b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Ether (C <sub>2</sub> H <sub>5</sub> OC <sub>2</sub> H <sub>5</sub> )	Bak and Sooryakumar (1994) sound speed	0.1–8100 MPa 25 °C	Brillouin scattering
bis( <i>m</i> -( <i>m</i> -phenoxy) phenoxy)-phenyl Ether (C <sub>36</sub> H <sub>26</sub> O <sub>5</sub> )	Swanson (1934) sound speed	0.1–9.4 MPa 23.6 °C	interferometer (196.6 kHz)
	Richardson and Tait (1957) sound speed, absorption	0.1–62 MPa 16–44 °C	ultrasonic pulse (3 and 12 MHz)
Ethyl acetate (C <sub>4</sub> H <sub>8</sub> O <sub>2</sub> )	Barlow <i>et al.</i> (1972) shear mechanical resistance	0.1–300 MPa 30 °C	torsional vibrating quartz (10, 30, and 450 MHz)
	Nomura <i>et al.</i> (1971) sound speed, <i>B/A</i> parameter	0.1–30.3 MPa 5–35 °C	ultrasonic interferometer (4 MHz)
Ethyl ether (C <sub>4</sub> H <sub>10</sub> O)	Ismagilov and Ermakov (1982) sound speed	0.1–2.5 MPa 89–138 °C	pulse echo (2.5 MHz)
Eugenol (C <sub>10</sub> H <sub>12</sub> O <sub>2</sub> )	Hawley <i>et al.</i> (1970) sound speed, absorption	0.1–381 MPa 30 °C	pulse echo (4.5 and 13.5 MHz regions)
Fluorobenzene (C <sub>6</sub> H <sub>5</sub> F)	Eden and Richardson (1960) sound speed, attenuation	0.1–55 MPa 22 °C	ultrasonic pulse (3 MHz)
Glycerol (C <sub>3</sub> H <sub>8</sub> O <sub>3</sub> )	Richardson and Tait (1957) sound speed, absorption	0.1–68.9 MPa 23 °C	ultrasonic pulse
	Litovitz <i>et al.</i> (1957); results also referred to in Litovitz and Carnevale (1958) absorption, relaxation frequency	0.1, 100 MPa 0 °C	pulse echo (17–75 MHz)
<i>n</i> -Heptane (C <sub>7</sub> H <sub>16</sub> )	Boelhouwer (1967) sound speed	0.1–140 MPa –20 to 200 °C	pulse echo (2 MHz)
	Takagi (1978a) sound speed	0.1–210 MPa 10–60 °C	pulse echo (1 MHz)
	Muringer <i>et al.</i> (1985) sound speed	0.1–263 MPa –88 to 37 °C	pulse echo (2 MHz)
	Melikhov (1985) sound speed	0.1–600 MPa 30–160 °C	pulse echo (4 MHz)



TABLE 1. Compilation of ultrasonic investigations as a function of pressure in organic liquids, including investigator, focus of investigators, pressure and temperature ranges of investigators' experimental work, and brief comments as to technique used by investigator(s) in obtaining experimental results (experimental frequencies noted where available)—Continued

Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
	Nakamura <i>et al.</i> (1995a) (1995b) sound speed	0.1–6000 MPa 26 °C	Brillouin scattering
1-Heptanol (C <sub>7</sub> H <sub>16</sub> O)	Sysoev and Otpuschennikov (1979) sound speed	0.1–811 MPa 15–180 °C	ultrasonic pulse (5 MHz)
Hexadecane (C <sub>16</sub> H <sub>34</sub> )	Boelhouwer (1967) sound speed	0.1–140 MPa –20 to 200 °C	pulse echo (2 MHz)
<i>n</i> -Hexadecane (C <sub>16</sub> H <sub>34</sub> )	Ye <i>et al.</i> (1990) sound speed, attenuation	0.1–70 MPa 30–120 °C	pulse echo (5 MHz)
<i>n</i> -Hexadecane+carbon dioxide (C <sub>16</sub> H <sub>34</sub> +CO <sub>2</sub> )	Ye <i>et al.</i> (1991) sound speed	5–50 MPa 20–60 °C	pulse echo (5 MHz)
	Ye <i>et al.</i> (1992a) sound speed	0.1–70 MPa 20–60 °C	pulse echo (5 MHz)
<i>n</i> -Hexadecane+ <i>n</i> -hexane (C <sub>16</sub> H <sub>34</sub> +C <sub>6</sub> H <sub>14</sub> )	Ye <i>et al.</i> (1992a) sound speed	0.1–70 MPa 25.2–100 °C	pulse echo (5 MHz)
Hexadecane+methane (C <sub>16</sub> H <sub>34</sub> +CH <sub>4</sub> )	Ye <i>et al.</i> (1991) sound speed	5–60 MPa 20–140 °C	pulse echo (5 MHz)
	Ye <i>et al.</i> (1992a) sound speed	8.5–66.2 MPa 19–140 °C	pulse echo (5 MHz)
<i>n</i> -Hexadecane+methane (gas) and carbon dioxide (gas) (C <sub>16</sub> H <sub>34</sub> +CH <sub>4</sub> +CO <sub>2</sub> )	Daridon <i>et al.</i> (1996) sound speed	12–70 MPa 40–120 °C	pulse echo (2 MHz)
Hexane (C <sub>6</sub> H <sub>14</sub> )	Boelhouwer (1967) sound speed	0.1–140 MPa –20 to 200 °C	pulse echo (2 MHz)
	Bohidar (1988a) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
<i>n</i> -Hexane (C <sub>6</sub> H <sub>14</sub> )	Eden and Richardson (1960) sound speed, attenuation	0.1–55 MPa 20 and 37 °C	ultrasonic pulse (3 MHz)
	Hawley <i>et al.</i> (1970) sound speed, absorption	0.1–392 MPa 30 °C	pulse echo (31.5 MHz)
	Allegra <i>et al.</i> (1970) sound speed, absorption	0.1–981 MPa 30 °C	pulse echo (12–40 MHz)
	Melikhov <i>et al.</i> (1976) sound speed	10–300 MPa 30–120 °C	pulse echo
	Takagi (1978a) sound speed	0.1–210 MPa 10–60 °C	pulse echo (1 MHz)
	Kagramanyan and Badalyan (1978) sound speed	0.1–203 MPa 30–100 °C	pulse echo (2.8 MHz)
	Melikhov <i>et al.</i> (1979) sound speed	0.1–588 MPa 30–150 °C	pulse echo (1–5 MHz)
	Ismagilov and Ermakov (1982) sound speed	0.1–2.5 MPa 111–186 °C	pulse echo (2.5 MHz)
	Melikhov (1985) sound speed	0.1–600 MPa 30–150 °C	pulse echo (4 MHz)
	Daridon <i>et al.</i> (1998b) sound speed	0.1–150 MPa 20–100 °C	pulse echo (3 MHz)

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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
<i>n</i> -Hexane+ <i>n</i> -decane (C <sub>6</sub> H <sub>14</sub> +C <sub>10</sub> H <sub>22</sub> )	Takagi and Teranishi (1985b) sound speed	0.1 MPa up to freezing line or 100 MPa 25 °C	pulse echo (2 MHz)
<i>n</i> -Hexane+ <i>n</i> -hexadecane (C <sub>6</sub> H <sub>14</sub> +C <sub>16</sub> H <sub>34</sub> )	Ye <i>et al.</i> (1992a) sound speed	8.5–66.2 MPa 19–140 °C	pulse echo (5 MHz)
Hexane+ <i>n</i> -propanol (C <sub>6</sub> H <sub>14</sub> +C <sub>3</sub> H <sub>7</sub> OH)	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Hexane+carbon tetrachloride (C <sub>6</sub> H <sub>14</sub> +CCl <sub>4</sub> )	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
<i>n</i> -Hexanol (C <sub>6</sub> H <sub>14</sub> O)	Sysoev and Otpuschennikov (1979) sound speed	0.1–811 MPa 15–180 °C	ultrasonic pulse (5 MHz)
	Pevnyi and Otpuschenikov (1980b) sound speed	0.1–811 MPa 20–170 °C	pulse echo (2 MHz)
Iodobenzene (C <sub>6</sub> H <sub>5</sub> I)	Eden and Richardson (1960) sound speed, attenuation	0.1–55 MPa 22 °C	ultrasonic pulse (3 MHz)
Insulin (dilute solution)	Bohidar (1989c) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
Methane (CH <sub>4</sub> )	Lacam (1956) sound speed	0.1–111 MPa 200 °C	diffraction of light by ultrasound (500 kHz)
	Van Itterbeek <i>et al.</i> (1967) sound speed	0.1–20 MPa –182 to –82 °C	pulse superposition
	Biswas and ten Seldam (1992) sound speed	100–1000 MPa –125 to 25 °C	pulse echo
	Shimizu <i>et al.</i> (1996) sound speed	0.1–5000 MPa 27 °C	Brillouin scattering
	Sasaki <i>et al.</i> (1996) sound speed	0.1–5000 MPa 27 °C	Brillouin scattering
Methane+hexadecane (CH <sub>4</sub> +C <sub>16</sub> H <sub>34</sub> )	Ye <i>et al.</i> (1991) sound speed	5–60 MPa 20–140 °C	pulse echo (5 MHz)
	Ye <i>et al.</i> (1992a) sound speed	8.5–66.2 MPa 19–140 °C	pulse echo (5 MHz)
Methane (gas)+hexadecane (liquid)+carbon dioxide (gas) (CH <sub>4</sub> +C <sub>16</sub> H <sub>34</sub> +CO <sub>2</sub> )	Daridon <i>et al.</i> (1996) sound speed	12–70 MPa 40–120 °C	pulse echo (2 MHz)
Methane (CH <sub>4</sub> ), gaseous+octane (C <sub>8</sub> H <sub>18</sub> )+gaseous propane (C <sub>3</sub> H <sub>8</sub> ) in ternary mixture	Daridon and Lagourette (1996) sound speed	25–100 MPa 22–100 °C	pulse echo (3 MHz)
Methanol (CH <sub>3</sub> OH)	Carnevale and Litovitz (1955) absorption, sound speed	0.1–196 MPa 30 °C	pulse echo (45 MHz)
	Eden and Richardson (1960) sound speed, attenuation	0.1–69 MPa 20 °C	ultrasonic pulse (3 MHz)

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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
	Wilson and Bradley (1964) sound speed	0.1–96 MPa 0–60 °C	ultrasonic pulse (5 MHz)
	Hawley <i>et al.</i> (1970) sound speed, absorption	0.1–413 MPa 30 °C	pulse echo (31 MHz region, 40.7 MHz)
	Bohidar (1988a) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Brown <i>et al.</i> (1988) sound speed	0.1–6800 MPa 25 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
	Lee <i>et al.</i> (1990) LA phonon velocity, lifetimes	0.1–8400 MPa room temperature	Brillouin scattering
	Nakamura <i>et al.</i> (1995a) (1995b) sound speed	0.1–6000 MPa 26 °C	Brillouin scattering
	Fujishiro <i>et al.</i> (1992) sound speed	0.1–6000 MPa 19–23 °C	Brillouin scattering
Methanol+ethanol (CH <sub>3</sub> OH+C <sub>2</sub> H <sub>5</sub> OH)	Bak and Sooryakumar (1994) sound speed	0.1–8100 MPa 25 °C	Brillouin scattering
Methanol+water (CH <sub>3</sub> OH+H <sub>2</sub> O)	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Methyl acetate (C <sub>3</sub> H <sub>6</sub> O <sub>2</sub> )	Biquard (1938) sound speed	25.8–63.2 MPa 17.5–19 °C	diffraction of light by ultrasound (10 MHz)
	Biquard (1939) sound speed	25.8–63.2 MPa 17.5–19 °C	diffraction of light by ultrasound (10 MHz)
	Nomura <i>et al.</i> (1971) sound speed, <i>B/A</i> parameter	0.1–30.3 MPa 5–35 °C	ultrasonic interferometer (4 MHz)
2-Methylbutane+pentane (C <sub>5</sub> H <sub>12</sub> +C <sub>5</sub> H <sub>12</sub> )	Houck (1974) sound speed	0.1–2400 MPa 22 °C	pulse echo (10 MHz)
Methylcyclohexane (C <sub>7</sub> H <sub>14</sub> )	Nakamura <i>et al.</i> (1995a) (1995b) sound speed	0.1–6000 MPa 26 °C	Brillouin scattering
Methyl ethyl ketone (C <sub>4</sub> H <sub>8</sub> O)	Atoyan and Mamedov (1975a) sound speed	0.1–162 MPa 0–200 °C	ultrasonic pulse echo (no frequency given)
Methyl hexylketone (C <sub>8</sub> H <sub>16</sub> O)	Atoyan and Mamedov (1975b) sound speed	0.1–162 MPa 10–200 °C	ultrasonic pulse echo (no frequency given)
Monochlorodifluoromethane (CHClF <sub>2</sub> ) (R22)	Takagi and Teranishi (1988b) sound speed	0.1–50 MPa 10–50 °C	pulse echo (2 MHz)
Monochloropentafluoroethane (C <sub>2</sub> ClF <sub>5</sub> ) (R115)	Takagi and Teranishi (1988b) sound speed	0.1–50 MPa 10–50 °C	pulse echo (2 MHz)
Monochlorodi fluoromethane +monochloropent-afluoroethane (CHClF <sub>2</sub> +C <sub>2</sub> ClF <sub>5</sub> ) (R502)	Takagi and Teranishi (1987b) sound speed	0.1–50 MPa 10–50 °C	pulse echo (2 MHz)
	Takagi <i>et al.</i> (1989a) sound speed	0.1–51 MPa 10–100 °C	pulse echo (2 MHz)
Monofluorotrichlor methane (CCl <sub>3</sub> F) (Freon11) (liquid)	Richardson and Tait (1957) sound speed, absorption	0.1–68.9 MPa 15 °C	ultrasonic pulse (1 MHz)

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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
Nitrobenzene (C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> )	Takagi (1975) sound speed	0.1–210 MPa 10–60 °C	ultrasonic pulse (1 MHz)
Nitrobenzene + aniline (C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> + C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> )	Takagi (1978b) sound speed	0.1–210 MPa 30 °C	pulse echo (1 MHz)
Nitrobenzene + benzene (C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> + C <sub>6</sub> H <sub>6</sub> )	Takagi and Teranishi (1982b) sound speed	0.1–200 MPa at 30 °C 30 MPa at 20–40 °C	pulse echo (1 MHz)
Nitrobenzene + benzonitrile (C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> + C <sub>7</sub> H <sub>5</sub> N)	Takagi and Teranishi (1988a) sound speed	0.1–100 MPa 25 and 30 °C	pulse echo (2 MHz)
Nitrobenzene + chlorobenzene (C <sub>6</sub> H <sub>5</sub> NO <sub>2</sub> + C <sub>6</sub> H <sub>5</sub> Cl)	Takagi and Teranishi (1984a) sound speed	0.1–200 MPa 20–40 °C	pulse echo (1 MHz)
Nitrogen (N <sub>2</sub> ) (gaseous) + <i>n</i> -octane (C <sub>8</sub> H <sub>18</sub> )	Daridon <i>et al.</i> (1994) sound speed	0.1–100 MPa 30–100 °C	pulse echo (3 MHz)
Nonane (C <sub>9</sub> H <sub>20</sub> )	Boelhouwer (1967) sound speed	0.1–140 MPa –20 to 200 °C	pulse echo (2 MHz)
<i>n</i> -Nonane (C <sub>9</sub> H <sub>20</sub> )	Melikhov (1985) sound speed	0.1–600 MPa 30–160 °C	pulse echo (4 MHz)
1-Nonanol (C <sub>9</sub> H <sub>20</sub> O)	Sysoev (1977) sound speed	0.1–101 MPa 20–200 °C	pulse echo (5 MHz)
1-Nonene (C <sub>9</sub> H <sub>18</sub> )	Badalyan <i>et al.</i> (1971) sound speed	0.1–118 MPa 30–140 °C	ultrasonic pulse (2 MHz)
Octamethylcyclotetrasiloxane (C <sub>8</sub> H <sub>24</sub> O <sub>4</sub> Si <sub>4</sub> )	Niepmann and Schmidt (1980) sound speed	coexistence line up to 60 MPa 27–177 °C	pulse echo (2 MHz)
Octane (C <sub>8</sub> H <sub>18</sub> )	Boelhouwer (1967) sound speed	0.1–140 MPa –20 to 200 °C	pulse echo (2 MHz)
	Badalyan <i>et al.</i> (1970) sound speed	0.1–118 MPa 30–140 °C	pulse echo (2 MHz)
	Takagi (1978a) sound speed	0.1–210 MPa 10–60 °C	pulse echo (1 MHz)
	Melikhov (1985) sound speed	0.1–300 MPa 30–120 °C	pulse echo (4 MHz)
	Daridon (1994) sound speed	5–100 MPa 20–100 °C	pulse echo (1–10 MHz)
<i>n</i> -Octane + <i>n</i> -dodecane (C <sub>8</sub> H <sub>18</sub> + C <sub>12</sub> H <sub>26</sub> )	Takagi and Teranishi (1985a) sound speed	0.1 MPa up to freezing line or 100 MPa 25 °C	pulse echo (2 MHz)
<i>n</i> -Octane (C <sub>8</sub> H <sub>18</sub> ) + gaseous nitrogen (N <sub>2</sub> )	Daridon <i>et al.</i> (1994) sound speed	0.1–100 MPa 30–100 °C	pulse echo (3 MHz)
Octane (C <sub>8</sub> H <sub>18</sub> ) + gaseous propane (C <sub>3</sub> H <sub>8</sub> ) + gaseous methane (CH <sub>4</sub> )	Daridon and Lagourette (1996) sound speed	25–100 MPa 22–100 °C	pulse echo (3 MHz)
1-Octanol (C <sub>8</sub> H <sub>18</sub> O)	Sysoev <i>et al.</i> (1976) sound speed	0.1–990 MPa 160–200 °C	pulse echo
1-Octene (C <sub>8</sub> H <sub>16</sub> )	Melikhov (1985) sound speed	0.1–300 MPa 30–120 °C	pulse echo (4 MHz)



TABLE 1. Compilation of ultrasonic investigations as a function of pressure in organic liquids, including investigator, focus of investigators, pressure and temperature ranges of investigators' experimental work, and brief comments as to technique used by investigator(s) in obtaining experimental results (experimental frequencies noted where available)—Continued

Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
	Badalyan <i>et al.</i> (1971) sound speed	0.1–118 MPa 30–140 °C	ultrasonic pulse (2 MHz)
Oil (blends)	Bohidar (1988b) sound speed	0.1–81.5 MPa 20 °C	Brillouin scattering
Oil (castor)	Barlow <i>et al.</i> (1973) viscoelastic properties	0.1–300 MPa –30 to 30 °C	torsional vibrating quartz (10–30 MHz)
Oil (diesel)	Talbott (1935) sound speed	4.1 MPa 0.17–98.9 °C	time required for induced pressure wave to reach end of pipe
Oil (distillation cuts)	Daridon <i>et al.</i> (1998b) sound speed	0.1–150 MPa 20–100 °C	pulse echo (2 MHz)
Oil (hydrocarbon)	Matteson and Vogt (1940) sound speed	3.4–41 MPa 14–99 °C	compressional waves (1 kHz)
Oil (hyperbaric reservoir fluid)	Daridon <i>et al.</i> (1996) sound speed	saturation pressure to 120 MPa 40–180 °C	pulse echo (3 MHz)
Oil (lubricating)	Barlow and Lamb (1959) shear, mechanical impedance	up to 100 MPa –56 to 30 °C	piezoelectric crystal (6–78 MHz)
	Nakamura <i>et al.</i> (1992) sound speed	0.1–3500 MPa	Brillouin scattering
Oil (naphtenic mineral oil)	Vergne and Roche (1991) sound speed	0.1–700 MPa 25–150 °C	falling body viscometer (1 MHz)
Oil (paraffinic and naphtenic oil)	Nakamura <i>et al.</i> (1994) sound speed	0.1–3000 MPa temp. not given	Brillouin scattering
	Nakamura <i>et al.</i> (1995a) sound speed	0.1–6000 MPa 26 °C	Brillouin scattering
	Nakamura <i>et al.</i> (1995b) sound speed	0.1–3000 MPa 26 °C	Brillouin scattering
Oil (petroleum)	Matteson (1938) adiabatic compressibility	12 MPa 49 °C	pressure waves
Oil (a variety of petroleum oils)	Wang <i>et al.</i> (1988) sound speed	0.1–20.6 MPa 22–75 °C	ultrasonic pulse 800 kHz
Oil (polymer oil systems)	Philippoff (1963) complex viscosity	0.1–103 MPa 25 °C	torsional vibrating quartz crystal (20 and 60 kHz)
Oil (real and synthetic heavy cut)	Daridon <i>et al.</i> (1998b) sound speed	0.1–150 MPa 20–100 °C	pulse echo (3 MHz)
Oil (spermaceti)	Goold <i>et al.</i> (1996) sound speed	0.1–9.1 MPa 22–38 °C	ultrasonic pulse (500 kHz)
Oil (synthetic heavy distillation cut; dilutions with hexane)	Daridon <i>et al.</i> (1998a) speed speed	0.1–150 MPa 20–100 °C	pulse echo (3 MHz)
Oil (three types of reservoir fluids: light hyperbaric oil, liquid-phase condensate gas, undersaturated heavy oil)	Daridon <i>et al.</i> (1998c) sound speed	10–120 MPa 0–180 °C	ultrasonic pulse (2 and 3 MHz)
Oil (aviation instrument) + 2-methylbutane	Houck and Heydemann (1971) sound speed	0.1–2000 MPa approximately room temperature	ultrasonic pulse

TABLE 1. Compilation of ultrasonic investigations as a function of pressure in organic liquids, including investigator, focus of investigators, pressure and temperature ranges of investigators' experimental work, and brief comments as to technique used by investigator(s) in obtaining experimental results (experimental frequencies noted where available)—Continued

Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
Penta-chlorobiphenyl and other chlorinated biphenyls (58%–42%) (Aroclor 1254)	Hutton <i>et al.</i> (1978) absorption, sound speed, viscoelasticity	0.1–260 MPa –87 to 90 °C	ultrasonic pulse (5–78 MHz)
1,1,1,2,2 Pentafluoro-3,3-dichloropropane (CF <sub>3</sub> CF <sub>2</sub> CHCl <sub>2</sub> )	Takagi and Fukushima (1998) sound speed	0.1–30 MPa 10–70 °C	pulse echo (2 MHz)
1,1,2,2,3 Pentafluoro-1,3-dichloropropane (CClF <sub>2</sub> CF <sub>2</sub> CHClF)	Takagi and Fukushima (1998) sound speed	0.1–30 MPa 10–70 °C	pulse echo (2 MHz)
Pentafluoroethane (HFC-125) (CHF <sub>2</sub> CF <sub>3</sub> )	Takagi (1996b) sound speed	saturation line to 30 MPa –30 to 60 °C	pulse echo (2 MHz)
Pentafluoroethane (HFC-125) and 1,1,1,2-tetrafluoro-ethane (HFC-134a) (CHF <sub>2</sub> CF <sub>3</sub> + CF <sub>3</sub> CH <sub>2</sub> F)	Takagi (1997b) sound speed, absorption	saturated pressure to 30 MPa –30 to 60 °C	pulse echo (2 MHz)
Pentafluoropropyl alcohol (5FP)	Takagi and Naguchi (1992) sound speed	0.1–70 MPa 10–75 °C	pulse echo (2 MHz)
Pentane (C <sub>5</sub> H <sub>12</sub> )	Swanson (1934) sound speed	0.1–11.2 MPa 23.9 °C	interferometer (197.7 kHz)
	Richardson and Tait (1957) sound speed, absorption	0.1–55 MPa 15–44 °C	ultrasonic pulse (3 and 12 MHz)
<i>iso</i> -Pentane (C <sub>5</sub> H <sub>12</sub> )	Eden and Richardson (1960) sound speed, attenuation	0.1–55 MPa 0–10.5 °C	ultrasonic pulse (3 MHz)
	Collings and McLaughlin (1970) viscosity	0.1–29.4 MPa 30–50 °C	torsional vibrating quartz (39 kHz)
<i>n</i> -Pentane (C <sub>5</sub> H <sub>12</sub> )	Collings and McLaughlin (1970) viscosity	0.1–68.6 MPa 30–50 °C	torsional vibrating quartz (39 kHz)
	Otpushchennikov <i>et al.</i> (1974a) sound speed	0.1–203 MPa 30–120 °C	ultrasonic pulse (2 MHz)
	Younglove (1981) sound speed	0.1–34 MPa –183 to 17 °C	pulse echo (10 MHz)
	Melikhov (1985) sound speed	0.1–600 MPa 30–160 °C	pulse echo (4 MHz)
	Belinskii and Ikramov (1973) sound speed, absorption, nonlinear parameters Ra and $\alpha_{ad}$	0.1–784 MPa 20, 30, 40 °C	ultrasonic pulse (13 MHz)
	Ismagilov and Ermakov (1982) sound speed	0.1–2.5 MPa 118–193 °C	pulse echo (2.5 MHz)
	Lainez <i>et al.</i> (1990) sound speed	0.1–210 MPa –10 to 160 °C	pulse echo (3 MHz)
Pentane + 2-methylbutane (C <sub>5</sub> H <sub>12</sub> + C <sub>5</sub> H <sub>12</sub> )	Houck (1974) sound speed	0.1–2400 MPa 22 °C	pulse echo (10 MHz)
1-Pentanol (C <sub>5</sub> H <sub>12</sub> O)	Sysoev <i>et al.</i> (1976) sound speed	0.1–990 MPa 20.6 and 150 °C	ultrasonic pulse
	Sysoev and Otpuschennikov (1979) sound speed	0.1–811 MPa 15–180 °C	ultrasonic pulse (5 MHz)
Polydimethylsiloxane	Takagi and Teranishi (1985a) sound speed	0.1–200 MPa 25, 30, and 35 °C	pulse echo (2 MHz)

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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
Polyethylsiloxane-2	Kagramanyan and Badalyan (1978) sound speed	0.1–203 MPa 30–100 °C	pulse echo (2.8 MHz)
	Kagramanyan and Badalyan (1979) sound speed	0.1–200 MPa 30–100 °C	pulse echo (2.8 MHz)
Polyethylsiloxane-3	Kagramanyan <i>et al.</i> (1978) sound speed	0.1–203 MPa 20–120 °C	ultrasonic pulse (2.8 MHz)
Polyethylsiloxane-2,3,4,6	Kagramanyan and Bagdasaryan (1983b) sound speed	0.1–600 MPa 30–100 °C	pulse echo (2.8 MHz)
Polyethylsiloxane-4,5	Kagramanyan <i>et al.</i> (1979) sound speed	0.1–203 MPa 30–100 °C	ultrasonic pulse (2.8 MHz)
Polymethylsiloxane (PMS-1000)	Sysoev and Otpuschennikov (1979) sound speed	0.1–507 MPa 20–180 °C	ultrasonic pulse (5 MHz)
Polystyrene latex suspension (in aqueous medium)	Bohidar (1989c) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
Propane (C <sub>3</sub> H <sub>8</sub> )	Lacam (1954) sound speed	0.1–111 MPa 25–225 °C	ultrasonic pulse (3–4 MHz)
	Noury (1954) sound speed	0.1–15 MPa 75–125 °C	diffraction of light (585 kHz)
	Lacam (1956) sound speed	0.1–111 MPa 200 °C	diffraction of light by ultrasound (500 kHz)
	Niepmann (1984) sound speed	coexistence line to 60 MPa –73 to 102 °C	pulse echo (2 MHz)
1,3-Propanediol (C <sub>3</sub> H <sub>8</sub> O <sub>2</sub> )	Sysoev and Otpuschennikov (1979) sound speed	0.1–861 MPa 19–180 °C	ultrasonic pulse (5 MHz)
1-Propanol (C <sub>3</sub> H <sub>7</sub> OH)	Carnevale and Litovitz (1955) sound speed, absorption	0.1–196 MPa 30 °C	pulse echo (25 MHz)
	Wilson and Bradley (1964) sound speed	0.1–96 MPa 0–60 °C	ultrasonic pulse (5 MHz)
	Hagelberg (1970) sound speed	0.1–98 MPa 30 °C	ultrasonic pulse (14.3 MHz)
	Hawley <i>et al.</i> (1970) sound speed, absorption	0.1–493 MPa 23–75 °C	pulse echo (22 and 31 MHz regions)
	Sysoev and Otpuschennikov (1976b) sound speed	0.1–990 MPa 15–150 °C	pulse echo (4 MHz)
	Sysoev and Otpuschennikov (1976a) sound speed	0.1–860 MPa 30 °C	pulse echo (4 MHz)
	Bohidar (1988a) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
2-Propanol (C <sub>3</sub> H <sub>7</sub> OH)	Sysoev and Otpuschennikov (1979) sound speed	0.1–861 MPa 17–150 °C	ultrasonic pulse (5 MHz)
	Pevnyi and Otpuschennikov (1980a) sound speed	162–608 MPa	ultrasonic pulse (1 and 10 MHz)
<i>n</i> -Propanal+hexane (C <sub>3</sub> H <sub>7</sub> OH + C <sub>6</sub> H <sub>14</sub> )	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering

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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
<i>n</i> -Proponal+toluene (C <sub>3</sub> H <sub>7</sub> OH+C <sub>7</sub> H <sub>8</sub> )	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
<i>n</i> -Propyl acetate (C <sub>5</sub> H <sub>10</sub> O <sub>2</sub> )	Nomura <i>et al.</i> (1971) sound speed	0.1–30.3 MPa 5–35 °C	ultrasonic interferometer (4 MHz)
Silicone (tetrachloro- phenylmethyl-polysiloxane)	Vergne and Roche (1991) sound speed	0.1–700 MPa 25–150 °C	falling body viscometer (1 MHz)
Silicone fluid (Dow Corning DC-703 and DC200)	McSkimin (1957) sound speed, absorption	0.1–359 MPa 5.6–50 °C	ultrasonic pulse (20 MHz)
Tetrachloromethane (CCl <sub>4</sub> )	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
<i>n</i> -Tetradecane+ <i>n</i> -decane (C <sub>14</sub> H <sub>30</sub> +C <sub>10</sub> H <sub>22</sub> )	Takagi and Teranishi (1985b) sound speed	0.1 MPa up to freezing line or 100 MPa 25 °C	pulse echo (2 MHz)
Tetraethoxysilane	Takagi <i>et al.</i> (1989b) sound speed	0.1–100 MPa 10–60 °C	pulse echo (2 MHz)
Tetraethylsilane	Takagi <i>et al.</i> (1989b) sound speed	0.1–100 MPa 10–60 °C	pulse echo (2 MHz)
1,1,1,2-Tetrafluoroethane (HFC-134a) (CF <sub>3</sub> CH <sub>2</sub> F)	Takagi (1996a) sound speed	saturation line to 30 MPa –30 to 60 °C	pulse echo (2 MHz)
	Guedes and Zollweg (1992) sound speed	saturation to 70 MPa –94 to 107 °C	pulse echo (3 MHz)
1,1,1,2-Tetrafluoroethane (HFC-134a) +pentafluoroethane (HFC-125) (CF <sub>3</sub> CH <sub>2</sub> F+CHF <sub>2</sub> CF <sub>3</sub> )	Takagi (1997b) sound speed, absorption	saturated pressure to 30 MPa –30 to 60 °C	pulse echo (2 MHz)
Tetrafluoropropyl alcohol (4FP)	Takagi and Naguchi (1992) sound speed	0.1–70 MPa 10–75 °C	pulse echo (2 MHz)
Tetramethylsilane	Takagi <i>et al.</i> (1989b) sound speed	0.1–200 MPa 10–60 °C	pulse echo (2 MHz)
Toluene (C <sub>7</sub> H <sub>8</sub> )	Swanson (1934) sound speed	0.1–30.4 MPa 25.0 °C	interferometer (172.0 kHz)
	Biquard (1938) sound speed	19.6, 38.7, 39.5 MPa, 18 and 20 °C	diffraction of light by ultrasound (10 MHz)
	Biquard (1939) sound speed, absorption	0.1–78.4 MPa 17.3–20 °C	diffraction of light by ultrasound (6.92 and 10 MHz)
	Hawley <i>et al.</i> (1970) sound speed, absorption	0.1–522 MPa 30 and 75 °C	pulse echo (22.5 MHz region)
	Allegra <i>et al.</i> (1970) sound speed, absorption	0.1–981 MPa 30 °C	pulse echo (12–40 MHz)
	Van't Klooster <i>et al.</i> (1980) sound speed	0.1–260 MPa –95 to 50 °C	pulse echo (2 MHz)



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Liquid	Investigator(s) Focus	Pressure Temperature range	Technique
	Takagi and Teranishi (1984c) sound speed	0.1–160 MPa 20, 25, and 30 °C	pulse echo (2 MHz)
	Muringer <i>et al.</i> (1985) sound speed	0.1–263 MPa –100 to 47 °C	pulse echo (2 MHz)
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Toluene + aniline (C <sub>7</sub> H <sub>8</sub> + C <sub>6</sub> H <sub>5</sub> NH <sub>2</sub> )	Takagi and Teranishi (1985c) sound speed	0.1–180 MPa 30 °C	ultrasonic pulse (1 MHz)
Toluene + benzene (C <sub>7</sub> H <sub>8</sub> + C <sub>6</sub> H <sub>6</sub> )	Takagi (1978c) sound speed	0.1–200 MPa 20, 30, and 40 °C	ultrasonic pulse (1 MHz)
Toluene + <i>n</i> -propanol (C <sub>7</sub> H <sub>8</sub> + C <sub>3</sub> H <sub>7</sub> OH)	Bohidar (1989b) sound speed	0.1–82.5 MPa 20 °C	Brillouin scattering
	Bohidar (1989a) impedance	0.1–80 MPa 20 °C	Brillouin scattering
Toluene + <i>o</i> -xylene (C <sub>7</sub> H <sub>8</sub> + C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub> )	Takagi and Teranishi (1985c) sound speed	0.1–180 MPa 30 °C	ultrasonic pulse (1 MHz)
Toluol (C <sub>7</sub> H <sub>8</sub> O)	Pevnyi and Otpuschennikov (1980a) sound speed	0.1–51 MPa 50 °C	ultrasonic pulse (1 and 10 MHz)
Trichlorofluoromethane (CFCl <sub>3</sub> ) (CFC-11)	Lainez <i>et al.</i> (1989) sound speed	0.1–210 MPa 80–140 °C	pulse echo (3 MHz)
	Takagi (1991) sound speed	0.1–75 MPa 10–100 °C	pulse echo (2 MHz)
Trichloromethane (CHCl <sub>3</sub> )	Takagi (1994a) sound speed	0.1–50 MPa 25–80 °C	pulse echo (2 MHz)
Triethylamine (C <sub>6</sub> H <sub>15</sub> N)	Litovitz and Carnevale (1958) absorption, relaxation frequency, sound speed	98 kPa, 196 MPa, 322 MPa 0 °C	pulse echo (14.9–65.3 MHz)
1,1,1-Trifluoroethane (CF <sub>3</sub> CH <sub>3</sub> )	Takagi (1997a) sound speed	0.1–30 MPa –30 to 60 °C	pulse echo (2 MHz)
Trifluoroethyl alcohol (3FE)	Takagi and Naguchi (1992) sound speed	0.1–70 MPa 10–75 °C	pulse echo (2 MHz)
<i>n</i> -Undecane (C <sub>11</sub> H <sub>24</sub> )	Melikhov (1985) sound speed	0.1–300 MPa 30–120 °C	pulse echo (4 MHz)
1-Undecanol (C <sub>11</sub> H <sub>24</sub> O)	Sysoev (1977) sound speed	0.1–101 MPa 20–200 °C	pulse echo (5 MHz)
Xylene (isomeric) + benzene (C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub> + C <sub>6</sub> H <sub>6</sub> )	Takagi (1981) sound speed	0.1–200 MPa 30 °C	ultrasonic pulse (1 MHz)
<i>o</i> -Xylene + benzene (C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub> + C <sub>6</sub> H <sub>6</sub> )	Takagi (1978c) sound speed	0.1–200 MPa 20, 30, and 40 °C	ultrasonic pulse (1 MHz)
<i>o</i> -Xylene + toluene (C <sub>6</sub> H <sub>4</sub> (CH <sub>3</sub> ) <sub>2</sub> + C <sub>7</sub> H <sub>8</sub> )	Takagi and Teranishi (1985c) sound speed	0.1–180 MPa 30 °C	ultrasonic pulse (1 MHz)

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